# Towards better perception

*A first perspective on the perception of operating force and cable displacement in shoulder harness controlled body powered prostheses*

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*A first perspective on the perception of operating force and cable displacement in shoulder harness controlled body powered prostheses*

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## Abstract

The available shoulder harness controlled prostheses do no fulfill the requirements of the users. It is unknown for which operating forces and cable displacements the user can make good use of proprioceptive feedback without feeling pain, discomfort or fatigue. These operating forces and cable displacements can be related to grasping forces and opening widths for activities of daily living to result in force and displacement transmission ratios for improved prosthetic design. The purpose of this research was to find operating force and cable displacement combinations that could be produced best without visual feedback. The force-displacement combinations were realized by a force task and interchangeable spring in the experimental setup. Thirty participants without arm defect wore a prosthesis simulator. They were first asked to *produce* a reference force with direct visual feedback of their operating force, next they were asked to *reproduce* this reference force without visual feedback. The error between visual produced value and blind *re*produced value was used to evaluate the results. Best reproduced operating forces were found between 24 and 32 N. Best reproduced cable displacements were dependent on the spring that was used; the larger the cable displacement was, the better the result. For larger forces it was more difficult to repeat the reference force-displacement. A perfect prosthesis should be operated by forces between 24 N and 32 N. It is important to take the amputee and their individual abilities into account as the results differ largely between participants.

243 words

## Clinical relevance

Better understanding of the perception of forces and displacements in prosthetic control contributes to the development of better prostheses.

19 words

## Introduction

Today's commercially available arm prostheses do not fulfill the requirements of the users. This is indicated by the high rejection rates; 26%-45% of body powered arm amputees reject their prosthesis.[1,2,3] The operating forces that most commercially available body powered prostheses require are too high.[4] High operating forces cause discomfort and pain to the user.[5,6] To satisfy the users with the performance of the shoulder harness the forces on the shoulder harness need to change.[7]

For control of prostheses different kinds of feedback are used (Figure 1); exteroceptive feedback (mostly vision and touch) and proprioceptive feedback from the remaining parts of the arm and shoulder (Golgi-tendon organs and muscle spindles). Information about the grasping force is fed back by Golgi tendon organs and tactile sensors in the skin; information about the opening width of the prosthesis is fed back by the muscle spindles and vision. Ideal control of prostheses does not involve a lot of effort; the mental load of the control should be as low as possible[3]. Compared to the subconscious control of a human limb, an important disadvantage of available prostheses is that the user is very dependent on visual feedback[8].The user can be relieved of the high mental load as a result of the visual feedback by better use of proprioceptive feedback.[3,8,9] Better use of proprioceptive feedback can improve the control of the prosthesis. It is unknown which cable displacements and operating forces give the best proprioceptive feedback information to the user.

Previous research, done by Hichert[10], focused on finding optimal operating forces for shoulder controlled prostheses, in which a human perceives the best feedback without feeling pain and getting exhausted. Hichert kept the cable displacements constant at 0 mm, this represents holding a rigid object. As an extension on the research of Hichert, this research includes cable displacements; it represents grasping a rigid or deformable object, the action before actual holding the object. The grasping force and opening width need to be altered correctly in order to grasp an object without dropping or deforming it.

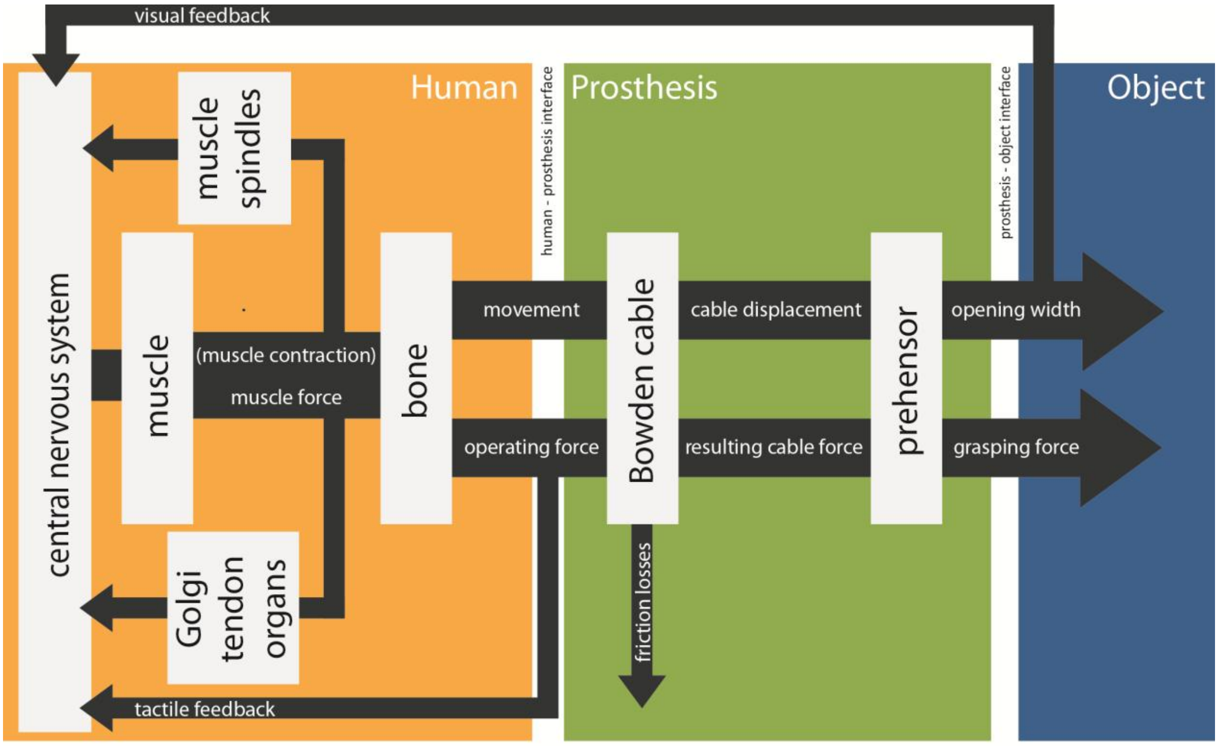


**Figure 1 Schematic overview of the control and feedback paths of prosthetic use as discussed in this research.**

## Approach

To investigate the perception of prosthetic use, the reproducibility of operating force and cable displacement combinations was measured. The force error between a visual produced value and blind reproduced value is a measure for the ability of a participant to control the operating forces and cable displacements with the shoulder harness. The experimental setup was based on the research for sensory weighting of force and position feedback[11] and the research for optimal operating forces of Hichert[10]. Reference values in this research were nine force-displacement combinations, realized by a force task and an interchangeable linear spring. From the force and the spring stiffness the cable displacements can be calculated. When eliminating visual feedback, only proprioceptive feedback and tactile feedback remain. Research into sensory weighting shows proprioceptive feedback plays a more important role than tactile feedback in force tasks[12].

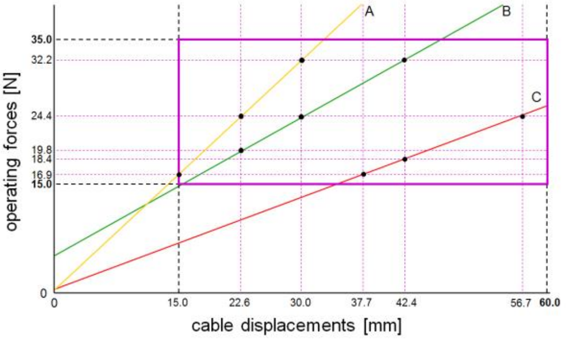


**Figure 2. Graph with the different linear springs and the window of the research which ranged from 15 to 35N and 15 to 60 mm. For the experiment 3 springs spread evenly in the window, the measurement points with different forces and displacements were chosen to be in relation to each other.**

Hichert[10] found optimal operating forces between 20-30 N, three out of seven participants with arm defect could not produce 30 N and four out of these participants could not produce 40 N. Because of unknown influences of added cable displacements the reference operating forces for this research ranged from 15 to 35 N.

Less is known about cable displacements. Preliminary experiments on different participants showed breathing had an influence on the produced cable displacement between 2 mm and 8 mm. Therefore, it was decided not to take a lower reference displacement than 15 mm. The upper boundary for the cable displacements was based on the maximum displacements of available prostheses, these range from 22 to 53 mm[4]. A maximum reference displacement was chosen 60 mm. The window with the boundaries of this research is shown in Figure 2. When using the linear relation between displacement and force in different linear springs, several force-displacement combinations in this window can be chosen.

The purpose of this research was to find the force-displacement combinations that could be reproduced best without visual feedback. The force-displacement combinations should not cause pain, discomfort or fatigue. It was hypothesized:

- the force error for the visual task would be very small, as the participants had direct visual feedback about their applied operating forces.

- The force error for the blind task (without visual feedback) would be smallest for a range of operating forces around 20-30 N, like Hichert found in the previous research[10].
- In the same line of thought, it was expected to find a range of optimal cable displacements as well.

Together they will indicate an area of optimal operating force and cable displacement combinations. Once these operating forces and cable displacements are known they can be related to the grasping forces and opening widths for activities of daily living (ADL). This results in force and displacement transmission ratios for improved prosthesis design.

## Method

*Participants*

Participants were persons without an arm defect. Different age groups are chosen; the younger group (range: 20-30 years, 10 male and 10 female) has full capacity of their muscle strength; for the older group (range: 51-61 years, 10 male) the muscle strength is assumed to be decreasing[13]. Measures (length, weight, length of dominant arm, length of back and shoulder width) are taken (Appendix 2.1) and compared to demographic data to see whether they are a good sample of the population. The prosthesis simulator was applied to the dominant side. The participants took part in all conditions of the experiment.

*Apparatus*

The experimental equipment consisted of a shoulder harness, a Bowden cable and a 'one fits all prosthesis simulator'. Cable displacements were possible by connecting the Bowden cable to a linear spring which was connected to the prosthesis simulator. To measure the operating forces and the forces on the spring two equal load cells (Feteris: FLLSB200 S-Beam junior) were used. The first load cell was connected to the Bowden cable on the back of the participant, between the shoulder blades. The second load cell was connected to the end of the Bowden cable and the spring. Both the load cells and a foot pedal with a micro switch were connected via an amplifier (Scaime: CPJ) and a data acquisition system (National instruments: NI USB-6008) to a laptop, which was running a LabVIEW program (version 9.0.1). Figure 3 shows a schematic overview of the measurement setup. The use of the measurement setup is shown in Figure 4. More details of the experimental setup are found in Appendix 3.

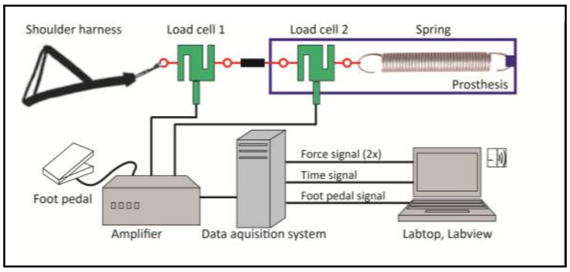


**Figure 3. Schematic overview of the measurement setup. The first load cell measured the operating forces (F_operating). The second load cell measured the forces on the spring (F_spring).**

*Procedure*

The participant was seated in a chair without arm rests, in front of a laptop screen and wore only a T-shirt or a long sleeve and sat up straight and relaxed. The participant was instructed to use (a combination of) abduction and anteflexion of the arm wearing the prosthesis simulator and shoulder protraction at the opposite side to accomplish the task. The participant was asked to move the arm with the simulator free in space and was not allowed to place the arm in his lap. During the

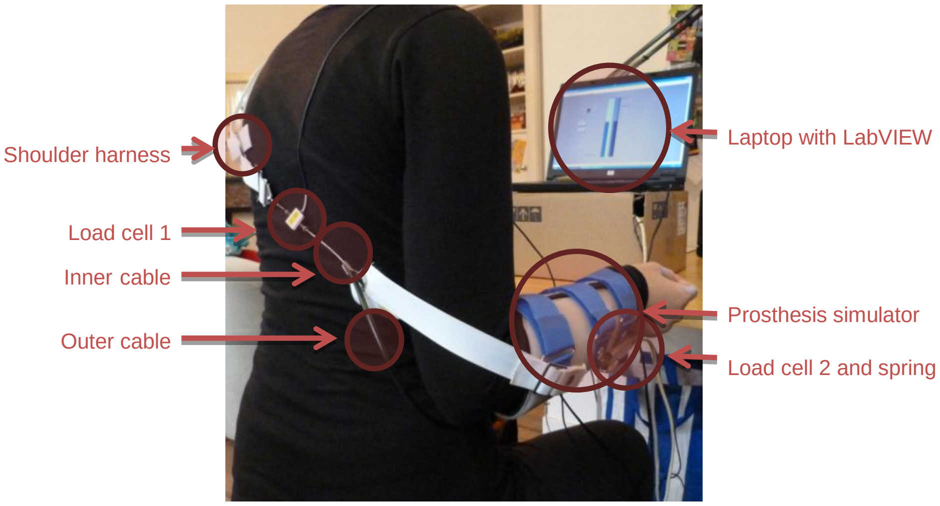


**Figure 4. Measurement setup in use during the experiments showing the positions of the shoulder harness, two load cells, the Bowden cable (inner and outer cable), the prosthesis simulator and the laptop with LabVIEW program.**

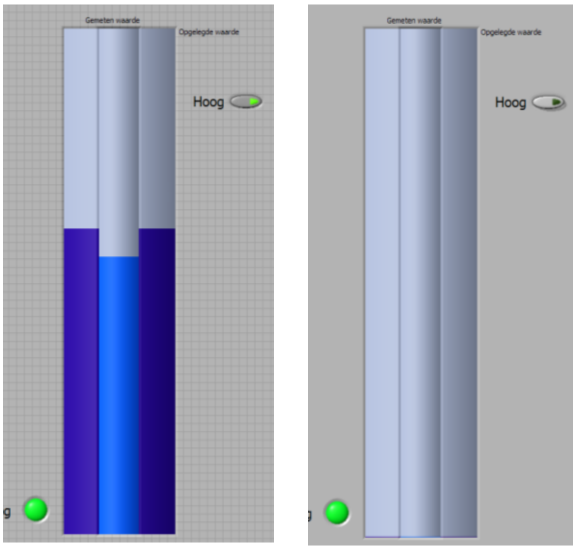


**Figure 6a&b. Front panels of the LabVIEW program for visual and blind blocks**
**Left: a) display for visual block**
**Right: b) display for blind Block**

experiment the participant was first requested, after hearing a beep, to produce a given force, this was presented as the vertical, outer bar on the display (Figure 5a). Via the first load cell, the value of their operating force was visualized on the display, presented as the inner vertical bar. When the participant was confident the requested value was equal to the measured value (as good as possible), a foot-pedal on the ground was pressed in. This marked a period of two seconds when the signal from the sensors was measured. The participant was asked to keep the force constant. After 2 seconds a beep indicated the participant could go back to a neutral position. This was a visual block.

Next a blind block started after a break of 3 seconds. The participant did not see the requested force or his measured force (Figure 5b). After hearing a beep, the participant tried to reproduce the force from the visual block. When he was confident the requested value was equal to his reproduced value, the foot-pedal was used again and after 2 seconds the neutral position was taken. These visual and blind blocks are repeated 11 times for each force. The sequence of the forces and the springs was randomized (Appendix 2.2). The values of the springs and forces were unknown to the participants. The height of the outer bar, indicating the requested force was the same for every force-displacement combination, the scale of the bars changed.

Following on every force-displacement combination, a NASA TLX questionnaire (paper version)(Appendix 7) was completed. At the start, during the two spring changes and at the end of the experiment the participants were asked to color a body map (Appendix 8). They colored the areas on the body where perception of touch (green), irritation (orange) or pain (red) occurred due to wearing the experimental equipment.

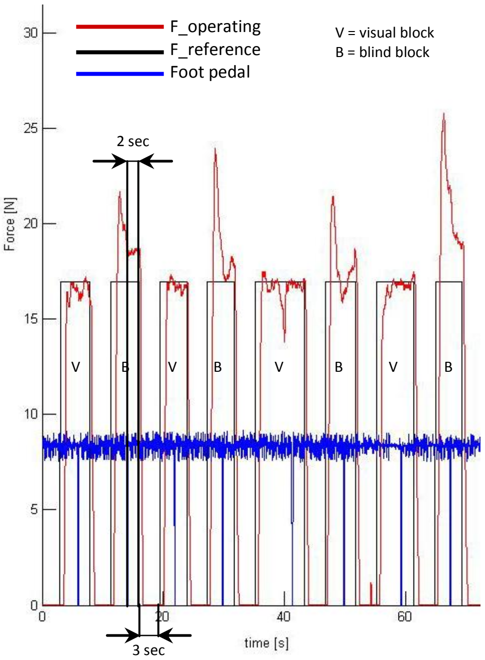


**Figure 5. Graph of the beginning of the results of one participant for a reference force of 16.9 N. In red the operating force is shown, in black the reference force and in blue it can be seen when the foot pedal is pushed. The durations of the blocks were not standard. For the results only the last two seconds were kept constant by the participant to calculate the means and standard deviations. The break between the blocks was three sec.**

*Data analysis*

From the data (Figure6) the last two seconds of the visual and blind blocks were evaluated. From these two seconds, the first second was deleted and only the last second was used for measurements. This was because multiple participants had trouble multitasking: keeping the force constant and pushing the foot pedal at the same time. This showed as a drop in the force signal. The first visual and blind blocks were deleted because of abnormality compared to the other blocks during the experiment for multiple participants (Appendix 9). For the last 10 visual and blind blocks the mean of F_operating of each block was calculated. For every force-displacement combination the mean and standard deviation were taken from these means.

**The visual error** is a measure for how well the participant could *produce* the force-displacement combination for all blocks. It gives information about the quality of visual feedback and the participants capabilities such as strength and reflexes. An optimal visual error is reached when

F_operating_visual is equal to the reference force, in practice this means the visual error is zero.

$$\text{Visual error} = \overline{(\bar{F}_{operating\_visual} - F_{reference})}$$

**The replication error** is a measure of how well the participant could *reproduce* the force-displacement combination for all blocks. The replication error gives information about the quality of proprioceptive and tactile feedback, taking participants capabilities in account. An optimal replication error is reached when the blind task is performed as good as the visual task, in practice this means were the replication error is zero.

$$\text{Replication error} = \overline{(\bar{F}_{operating\_blind} - \bar{F}_{operating\_visual})}$$

To compare the different combinations to each other the relative visual error and replication error were calculated.

$$\text{Visual error relative} = \frac{\overline{(\bar{F}_{operating\_visual} - F_{reference})}}{F_{reference}}$$

$$\text{Replication error relative} = \frac{\overline{(\bar{F}_{operating\_blind} - \bar{F}_{operating\_visual})}}{\bar{F}_{operating\_visual}}$$

Because results around zero are expected the visual error and replication error will not give sufficient information about the size of the error. The average is taken over all blocks and all participants; positive and negative errors average towards zero. The error might appear lower because of this. By calculating the absolute values of the visual and replication error this information can be provided.

**The repetition** gives an impression of how well the participant could (re)produce the same force-displacement combination every block. The repetition is optimal when the differences between (re)produced forces of the blocks are zero.

$$\text{Visual repetition} = \sigma_x\overline{(\bar{F}_{operating\_visual} - F_{reference})}$$

$$\text{Blind repetition} = \sigma_x\overline{(\bar{F}_{operating\_blind} - F_{reference})}$$

The participant gave his opinion about the workload he experienced in the NASA TLX questionnaire. From this frustration levels, confidence and effort in the outcome of the task were measured. For the evaluation of the NASA TLX the answers were rated and averaged over all participants. From the body map irritation because of one of the springs and in time can be analyzed. This was done by counting the irritating and painful areas and checking whether a specific spring had influence on these counts.

To investigate the statistical significance SPSS was used. A significance level of 0.05 was maintained for the repeated measures ANOVA and the mixed ANOVA. Dependent variables were the visual error, replication error and the repetition. The independent variables were the force-displacement combinations.

**Results**

No significant differences were found between the different age groups and gender of the participants (Table 1). No learning effects were found for the blocks of a force-displacement combination and between all combinations of the experiment.

*Visual error*

The visual error for the force-displacement combinations is shown in Figure 7. Different colors indicate the different springs that were used. The visual error represents the ability to *produce* a force-displacement combination. It is the deviation of the visual operation force and the reference force. The plane in the 3D plot shows where the visual operating force and the reference force are equal. A visual error below this plane indicates the visual operating force is smaller than the reference force. Figure 8 shows the relative visual error.

The smallest visual errors are found for 16.9 N, 18.4 N and 19.8 N, post hoc tests revealed significant differences for the force line of 16.9 N with the force lines 24.4 N (p = .001) and 32.2 N (p=.000). For each separate spring, the smallest displacement has the smallest visual error. The visual error represents 0.5% to 1.5% of the requested reference force. The error bars in the plot indicate the standard deviations over the group of participants. The magnitude implies a high deviation between participants.

The absolute visual error has significant differences for the 9 combinations. Post hoc tests revealed significant differences for the combinations on the 16.9N, 18.4 and 19.8 N force lines and the other force lines, except for the combination (16.9N; 14.0 mm). For the absolute visual error the smallest reference displacement of the spring has the smallest visual error. The absolute visual errors are all between 2 and 2.5% of the reference force.

*Replication error*

The replication error for the force-displacement combinations is shown in Figure 9. The replication error represents the ability of a participant to *reproduce* the force-displacement combination. This is the deviation of the blind operating force and the visual operation force. The plane in the 3D plot shows where the blind operation force is equal to the visual operation force. A replication error closer to the plane indicates a better performance. Figure 10 shows the relative replication error.

The smallest replication errors are found for 24.4 N and 32.2 N, also for the relative error. The largest replication errors can be found between 16.9 and 19.8 N. Post hoc tests reveal the differences between the largest and the smallest replication errors are significant. For the different springs the replication error is smaller for a larger displacement. From the error bars in the figure can be seen that the difference between participants does not differ for the force-displacement combinations.

The absolute replication error has little significant differences between the combinations; according to post hoc tests only the combinations (32.2N, 26 mm) and (24.4 N, 30.8mm) differ. For the relative absolute replication error the combination (16.9N, 14.0 mm) has the biggest replication error. The other errors do not differ significantly according to the post hoc tests.

*Repetition*

Figure 11 shows the visual and blind repetition for every spring. The repetition represents the ability of the participant to constantly (re-)produce a force-displacement combination for several times. It is the average for all participants of the standard deviations of the mean visual and blind operating forces. There are no significant differences for the visual repetition. The blind repetition shows differences between the different force lines; it is higher for the larger forces. The relative blind repetition does not show significant differences. The visual repetition and blind repetition differ significantly. The standard deviations over the group of participants for the repetition are small.

*Opinion of the participants*

All 30 participants filled out the NASA TLX questionnaire after every force-displacement combination (nine in total). No significant differences occurred comparing the mean differences for every force-displacement combination. For all combinations the frustration was low to very low. For all combinations the confidence in the performance was medium high. For all combinations the effort (mental demand, physical demand and effort) was low. Temporal demand was low during the whole experiment; the participants did not feel rushed. The results have large standard deviations over the group of participants; this indicates there are large differences between the participants.

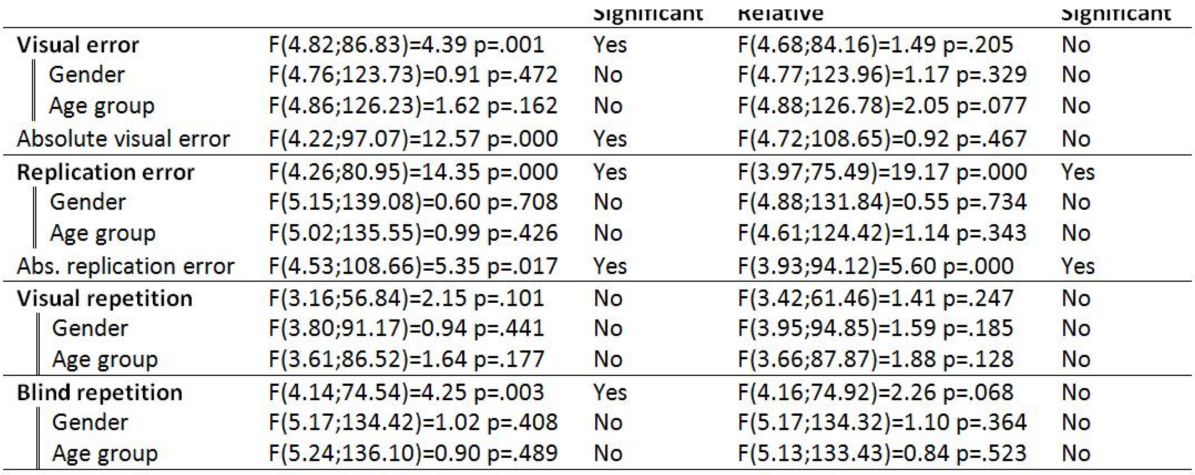
The body map was colored by 24 of the 30 participants. Thirteen participants indicated irritation sections. The sections that were irritated were the upper part of the socket of the prosthesis simulator, the loop of the shoulder harness and more specific the armpits. For one participant the irritation in the armpits resulted in a pain at the end of the experiment.

*Demographic data*

There were some differences between the demographic data and the measures from the participants. The younger group was significantly heavier than normal Dutch students[14]. They also had slightly longer upper bodies. For the overall conclusion it can be said the participants were a reasonable sample of the population.

There were no measures of a population of persons with arm defects available, so no comparisons could be made to compare the participants to persons with arm defects.

**Table 1. Significance between the nine force displacement combinations for the visual and replication error and absolute visual and replication error , the visual and blind repetition and significance between male and female and the young and the older group of participants**



| | | Significant | Relative | Significant |
|---|---|---|---|---|
| **Visual error** | F(4.82;86.83)=4.39 p=.001 | Yes | F(4.68;84.16)=1.49 p=.205 | No |
| Gender | F(4.76;123.73)=0.91 p=.472 | No | F(4.77;123.96)=1.17 p=.329 | No |
| Age group | F(4.86;126.23)=1.62 p=.162 | No | F(4.88;126.78)=2.05 p=.077 | No |
| Absolute visual error | F(4.22;97.07)=12.57 p=.000 | Yes | F(4.72;108.65)=0.92 p=.467 | No |
| **Replication error** | F(4.26;80.95)=14.35 p=.000 | Yes | F(3.97;75.49)=19.17 p=.000 | Yes |
| Gender | F(5.15;139.08)=0.60 p=.708 | No | F(4.88;131.84)=0.55 p=.734 | No |
| Age group | F(5.02;135.55)=0.99 p=.426 | No | F(4.61;124.42)=1.14 p=.343 | No |
| Abs. replication error | F(4.53;108.66)=5.35 p=.017 | Yes | F(3.93;94.12)=5.60 p=.000 | Yes |
| **Visual repetition** | F(3.16;56.84)=2.15 p=.101 | No | F(3.42;61.46)=1.41 p=.247 | No |
| Gender | F(3.80;91.17)=0.94 p=.441 | No | F(3.95;94.85)=1.59 p=.185 | No |
| Age group | F(3.61;86.52)=1.64 p=.177 | No | F(3.66;87.87)=1.88 p=.128 | No |
| **Blind repetition** | F(4.14;74.54)=4.25 p=.003 | Yes | F(4.16;74.92)=2.26 p=.068 | No |
| Gender | F(5.17;134.42)=1.02 p=.408 | No | F(5.17;134.32)=1.10 p=.364 | No |
| Age group | F(5.24;136.10)=0.90 p=.489 | No | F(5.13;133.43)=0.84 p=.523 | No |

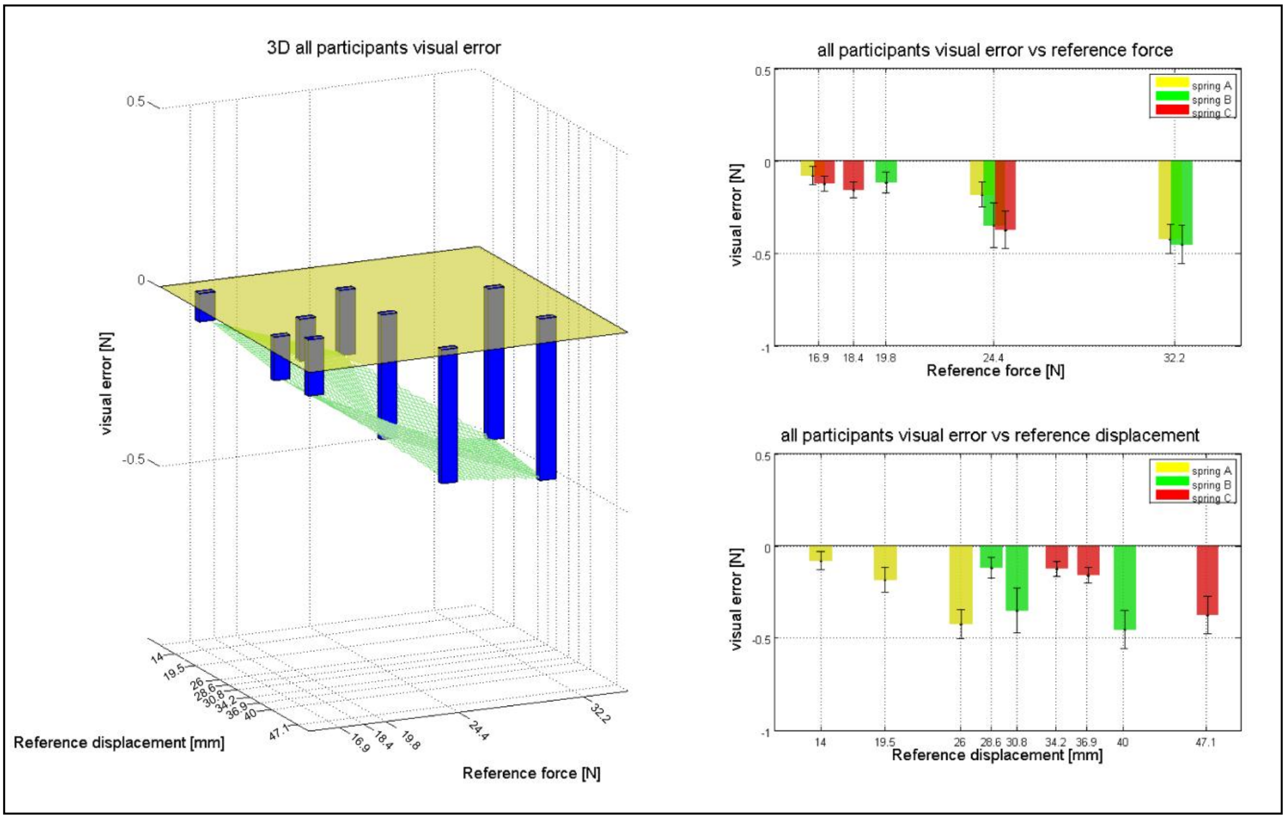


**Figure 7. Visual error for all participants**
**Left: 3D plot shows the visual error for the force-displacement combinations.**
**Upper right: the visual error for the reference forces, lower right: the visual error for the reference displacements**
**Error bars: the standard errors across the results of the group of participants**

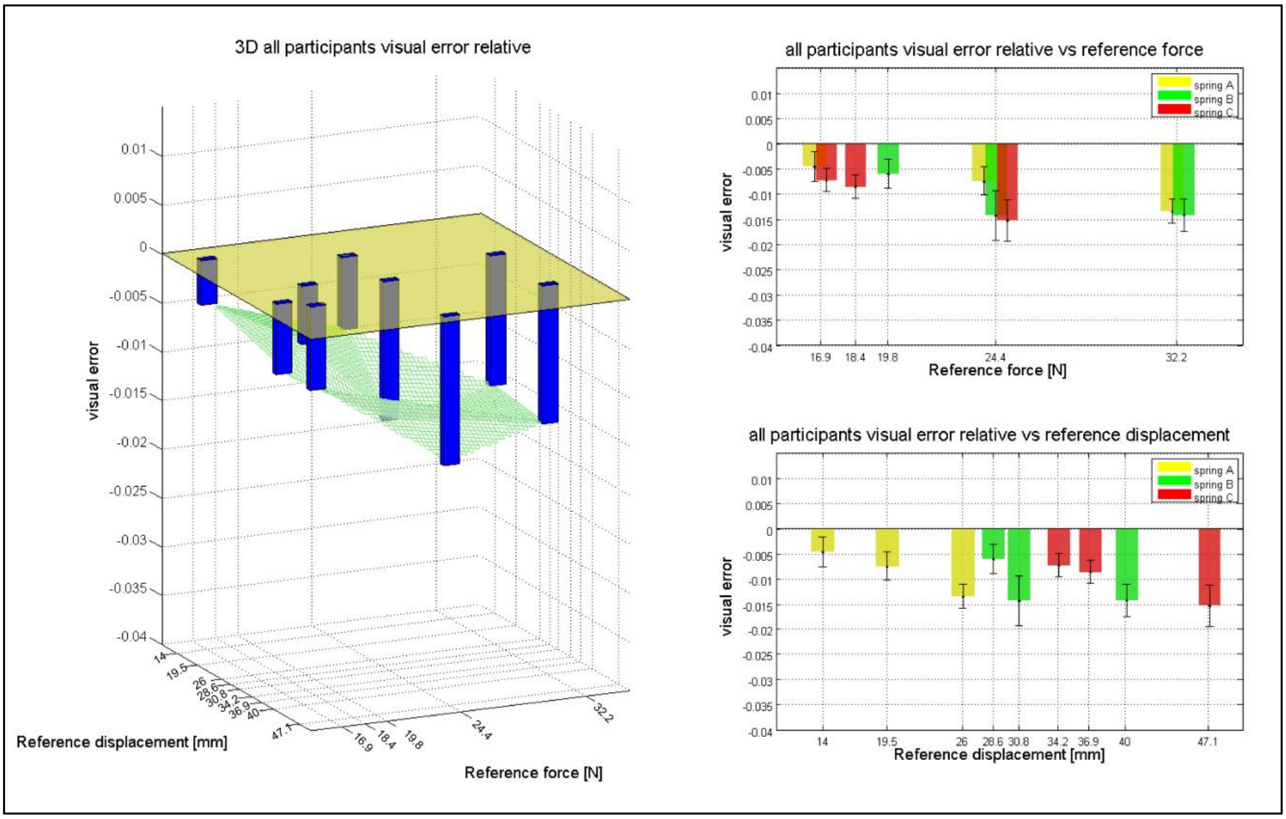


**Figure 8. Relative visual error for all participants**
**Left: 3D plot shows the relative visual error for the force-displacement combinations.**
**Upper right: the relative visual error for the reference forces, lower right: the relative visual error for the reference displacements**
**Error bars: the standard errors across the results of the group of participants**

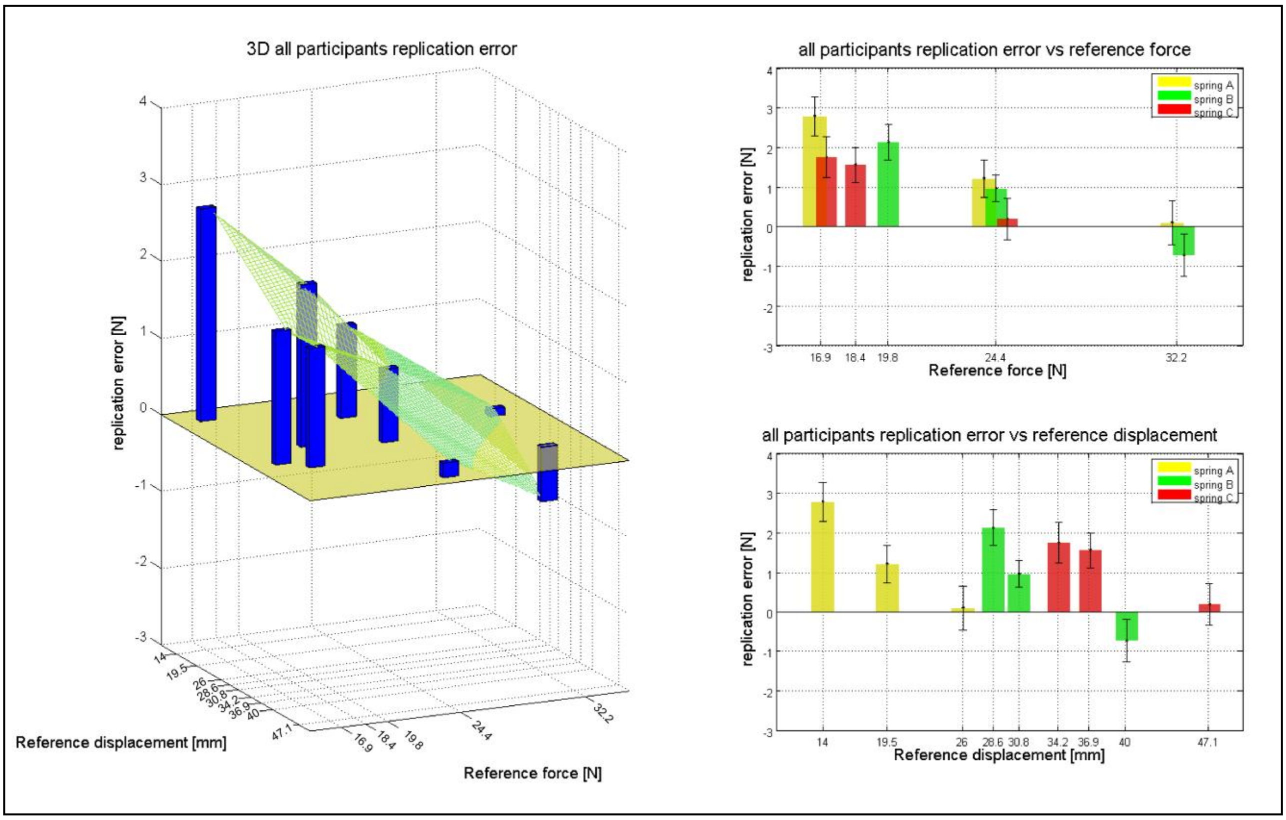


**Figure 9. Replication error for all participants**
**Left: 3D plot shows the replication error for the force-displacement combinations.**
**Upper right: the replication error for the reference forces, lower right: the replication error for the reference displacements**
**Error bars: the standard errors across the results of the group of participants**

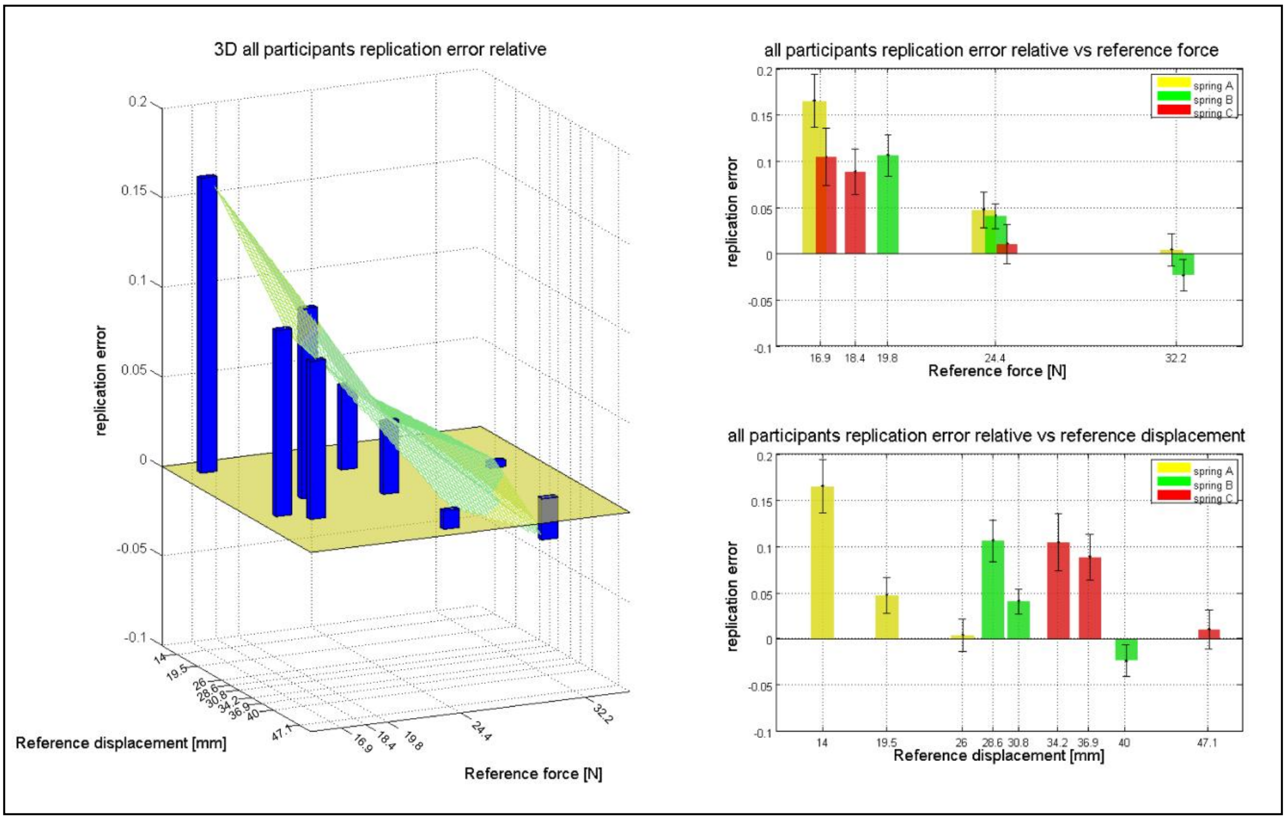


**Figure 10. Relative replication error for all participants**
**Left: 3D plot shows the relative replication error for the force-displacement combinations.**
**Upper right: the relative replication error for the reference forces, lower right: the relative replication error for the reference displacements**
**Error bars: the standard errors across the results of the group of participants**

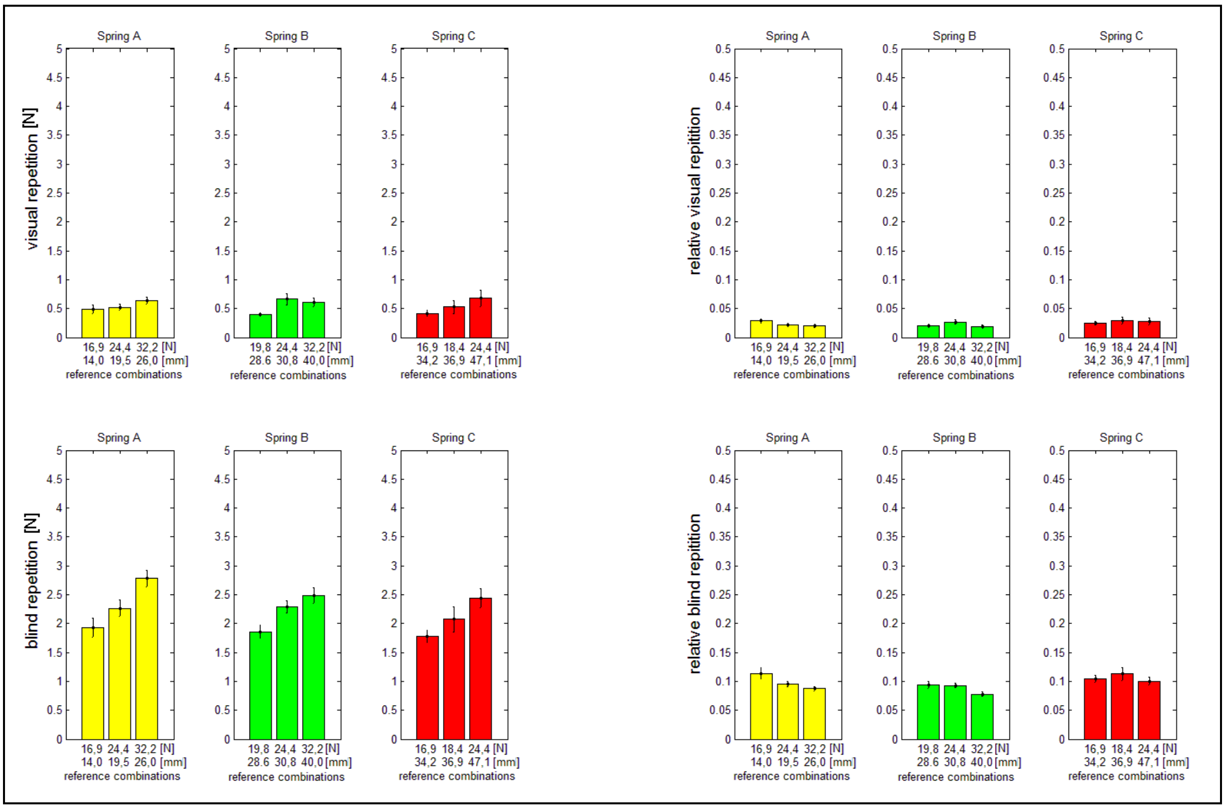


**Figure 11. Repetition for all participants (SD of the mean visual and blind operating forces)**
**Upper left: visual repetition Upper right: Relative visual repetition**
**Lower left: blind repetition Lower right: relative blind repetition Error bars: standard error of the repetition**

## Discussion

As hypothesized producing a reference force-displacement combination with visual feedback is a task participants could execute well for the overall experiment. This can be said because the visual errors were low; maximum 1,5 % of the reference force for the visual error and between 2 and 2.5% for the absolute visual error. It was done best for the lower reference forces and displacements (depending on the spring).

The purpose of this research was to find the force-displacement combinations that could be *re*produced best without visual feedback. A good result is indicated by a small replication error. For a small replication error better use of proprioceptive feedback was assumed, taken into account the participants' capabilities on the force and displacement level. The replication error was smallest for operating forces around 24 to 32 N. This is in line with the expectations adapted from the prior research of Hichert[10]; it was hypothesized the replication error would be smallest for a range of operating forces around 20-30 N. In the same line of thought, it was expected to find a range of optimal cable displacements as well. This was not the case, as the best results for the displacements were dependent on the spring used. For each spring applied; the larger the reference displacement was, the better the result. For this experiment a linear spring was used, for prosthetic use this is the prehensor device and the object being held. Figure 12 shows the expected optimal area of the replication error for reference displacements and reference forces. The green area indicates the area between the combinations were replication errors were low; here good use of proprioceptive feedback was assumed. The red area indicates the area between the combinations

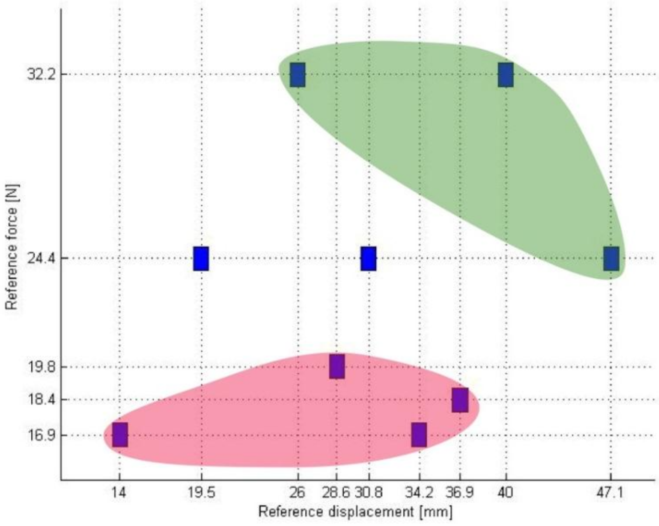


**Figure 12. Map with the nine force displacement combinations. In green the area is indicated between the combinations with the best use of proprioceptive feedback. In red the area is indicated between the combinations were use of proprioception was significantly less.**

where the replication error was significantly higher; here the use of proprioceptive information is assumed to be less. In the red area the reproduced combinations had an average absolute error of 15 to 20% of the visual operating force, for the green area this was only 10 to 12%. Translating this to prosthetic use it means for the green area the control without visual feedback over the operating force and cable displacement is better, resulting in a better controlled grasping force and opening width.

Without visual feedback it is more difficult to repeat the same force several times and to repeat higher forces than lower forces. Without visual feedback a person can reproduce an error which is 10% more (or less) than the intended force, when grasping an object, for optimal forces between 24 to 32 N this means 2,4 to 3,2N. The repetition can add up to the replication error and cause problems when trying to precisely operate a prosthetic device. For now it is uncertain which force and displacement offsets are tolerable during ADL. Earlier research gives some indications[15]; e.g. holding a milk carton requires a pinch force of 7.8 N, spilling the milk out of the carton occurs for forces of 16.8 N and higher, this is an increase of 9 N. This means an error up to 115% of the intended force of 7.8N is possible without spilling milk . For the 10-12% error and added 10% offset of the operating force the total error is 20-22%; there will be no milk spilled. When more research is done, it can be confirmed the offsets for the optimal operating forces and cable displacements found, are acceptable.

### *Different force-displacement combinations*

The intention of this research was to use nine force-displacement combinations which had relations to each other as can be seen in Figure 2. Because of friction losses of the experimental setup, the forces on the linear spring are not the same as the operating forces. This causes the displacements of the reference force-displacement points to shift. The actual reference points are shown in Figure 13.

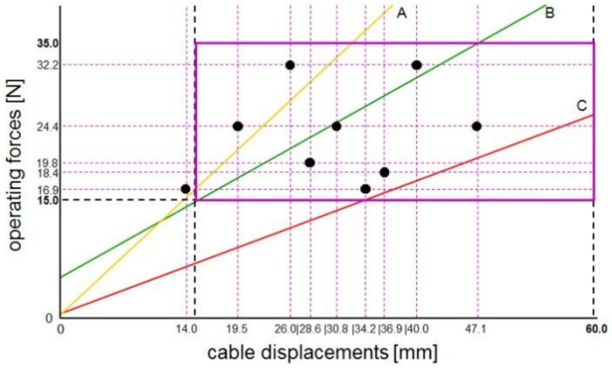


**Figure 7. Actual force-displacement combinations next to the used springs. The previous points were positioned on the intersection of the spring line and the same force-line as the actual combination.**

### Friction losses

During the experiments the maximum friction losses were 46% (SD = 10.5%) averaged over all participants and all force- displacement combinations (Appendix 10). The friction is due to moving parts of the Bowden cable and the experimental setup. Friction losses of the Bowden cable are difficult to predict as they depend on the radius and degrees of curvature of the Bowden cable[16]. From literature an estimation of the friction losses of the Bowden cable can be made around 20%[16]. Friction losses did not change in the process of the experiments. To avoid the influences of the experimental setup the operating forces were measured as closely as possible to the shoulder harness. The friction losses found were large; this is a common problem when using a Bowden cable. Investigation why the friction losses of the experiment were high and whether the friction losses are comparable to prosthetic use, makes clear friction losses of the experimental setup were acceptable or not. When friction losses are unacceptable, the experimental setup needs to change for follow-up research.

### *Grasping forces and opening widths*

Relating optimal operating forces and cable displacements with grasping forces and opening widths will lead to design criteria for improved prosthetic design. It is possible a transmission ratio with variable gain is needed.

The findings for optimal operating forces in this research confirm the findings of Hichert[10]; the TRS hook is the only voluntary closing prosthesis that can be operated in the found force range of 24-32 N. The cable displacements of the TRS hook have a maximum of 49 ± 0.1 mm[4], which is in line with the findings for the optimal cable displacements. Still the TRS hook is not ideal, because for operating forces of 30 N a pinch force around 13 N is created. For ADL, pulling on a sock requires the highest pinch force of 34.3 N[17]. To achieve this pinch force an operating force of 60 N is needed[4]. The outcomes of this research (and follow-up research) need to be applied to new prosthesis design in order to lower the high operating forces.

Next to research into the input of the new prosthesis design, more insight into the outputs of this system is also required to know the criteria for new design. More information about the grasping forces and opening widths of ADL can provide the

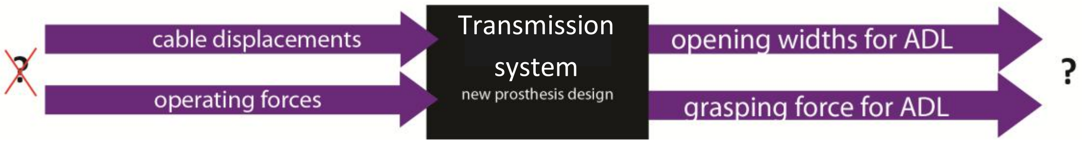


**Figure 14. Black box of new prosthesis design. The input is being investigated: operating forces and cable displacements. When also the output is known (opening widths and grasping forces for ADL) it is possible to design the transmission system for shoulder controlled prosthesis with improved cable control.**

needed information to design the transmission system from Figure 14. For this experiment the transmission system was a single linear spring, because all transmissions in the prosthetic prehensors on the market[4] were linear. It is possible the optimal input and output cannot be matched with a single linear transmission ratio. Because of different optimal transmission ratios between operating force and grasping force and cable displacement and opening width, a transmission ratio with a variable gain can be needed. When grasping an object first good control over opening width is needed, second good control over the grasping force is needed. Because these actions can be seen separate, different gains can be used. The influence of non-linear transmissions is unknown, as well as the abilities of a human coping with nonlinear relationships in prostheses. To see whether prosthetic users can cope with transmission ratios with a variable linear gain or more complex nonlinear relations more research is needed.

*Over- and underestimation of force tasks*

Research from Shergill et al[18] into force replication tasks suggests overestimation of a reference force in force tasks to be a natural side effect of neural processing. For this research this was not the case as the highest tested force of 32.2 N was underestimated in the blind blocks. Some participants even underestimated all requested forces. Research from Hichert[10] also found higher reference forces to be under estimated compared to overestimated lower forces. Hichert suggests the underestimation of the produced forces is because of a lack of the participant's strength; this suggestion is supported by this research.

*Large differences between participants*

When a person is in need of a prosthesis it is important to take the individual abilities into account. For all results of the visual and replication error large deviations between participants make the average results inaccurate. Participants were very variable; the optimum cable force and displacement for one participant could be completely different for another participant. More detail into the optima per participant will give better insight. Additional research for specific sub-groups for age, gender, weight and arm length did not show any significant influences on the results. Also the results from the NASA TLX questionnaires and the body map were very dependent on the participant, as can be understood from the large standard deviations. From this it might be concluded there are no optimal operating forces and cable displacements for all participants. A possibility is to generate a clinical method which is capable of determining the optimal operating forces and cable displacements for a specific patient to see which available prosthesis is best suited for this particular patient.

*Perception and memory*

The method for determining good proprioceptive feedback with visual and blind blocks is not only based on the ability of a participant to reproduce forces and displacements, but is also based on the ability of perception of these forces and displacements. Next to the proprioceptive and tactile feedback during a blind block also the quality of the feedforward information is of interest. The feedforward information (controlling the system in a pre-defined way) of the blind block is dependent on the perception of forces and displacements (visual, tactile and proprioceptive feedback) from the previous visual block. Using the visual/blind method for this experiment makes the results dependent on the 'memory function' of the central nervous system. For the results of this experiment it is unknown how substantial the influence of this memory effect is and if the influence changes for different force-displacement combinations. Testing for good use of proprioceptive feedback without the perception part is possible by giving different force and position perturbations next to eliminating visual feedback and tactile feedback (numbing the skin). An unreliable signal will be ignored by the central nervous system, this way only position or force feedback can be researched and additional information about the sensory weighting during the use of prostheses is researched as well. The multiple degrees of freedom in this experimental setup will most likely be scarified, because of the dependence of a connection to a pertubator.

*Fatigue and mental load*

Not all requirements for optimal operating forces and cable displacements were researched. The effects of holding an object for a longer time (fatigue) and mental load are unknown. This research did not go into the details whether reproducing a force displacement combination was exhausting over time. The measurement time (two seconds) was not long enough to see the effects of fatigue when holding an object for a longer time. Further research could ask the participants to keep the requested force-displacement combination constant for a longer period of time. The average of the standard deviation for the operating force will give information about how constantly leveled a certain combination was, per block. The requirement of low mental load for control can be doubted because the participants were only concentrating on completing the task. The mental load for the blind blocks was not tested and could have been high because no other mental demanding assignments were given during the test. From the results it was seen multitasking (using the foot pedal and keeping the force constant) had an impact on the performance of the participant. More research into what the effects are of distracting the participant during the task can give more understanding into the mental load for different force-displacement combinations.

*Follow-up research*

Follow-up research should include new research areas and position tasks. It is advised to define the research window more precise before follow-up research is done. The operating force and cable displacements for the upper boundaries of the research should be defined (Figure 15): first the maximum operating forces and cable displacements should be measured. For this research the maximum operating force of the participants was not measured because of the limited force sensor (max. load of 111N). From literature the maximum operating force was found to be 280 N[19]. Preliminary results of recent research of Hichert indicate participants can produces even higher operating forces. Next the percentage of the maximal forces and displacements which are suitable for ADL without exhausting the user needs to be researched. From literature it is found a suitable force for ADL was estimated to be 15-20% of the maximum muscle force[20]. For the maximum operating forces from literature this means forces from 42 to 56 N can be used without exhausting the user. Forces of 40N were found uncomfortable[10], finding maximum operating forces did not change the upper boundary set for this research. For the cable displacements of the upper boundary this is not known yet, and needs to be investigated. For now the reference cable displacements are based on the available prosthetics, not on the abilities of the participants themselves. It is possible the experiment did not find the optimal results because the research window was too small. It is also useful to test for different thresholds for force and position feedback, to see between which reference force-displacement combinations the feedback do not differ as perceived by the participant.

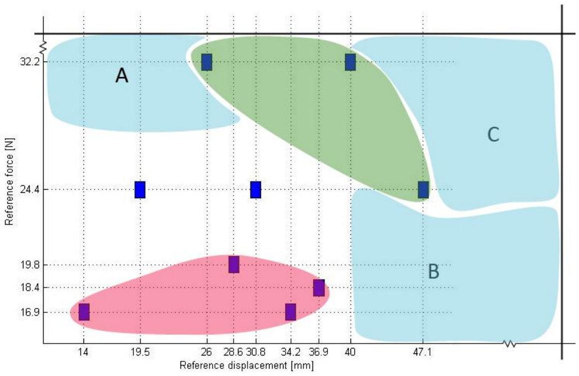


**Figure 15. Rough indications for new research areas A, B and C. To research these areas it is advised to research the upper boundaries of the operating force and cable displacements first (thick black lines).**

Because the perception of cable displacements is dependent on the spring used, it is advised to investigate other springs to see if the area in Figure 15 marked with ‘A’ is also optimal. Area B indicates lower operating forces than found good perceived in this research, but combined with high cable displacements they might give good results too. For area C the range of operating forces is good perceived according to this research; however it is unknown whether the perception of operating forces is still good for larger cable displacements.

The focus of this research was a force task, using a force sensor to calculate the error. To know the effect of position tasks for the researched area (and the new research areas A, B and C) the same study can be repeated changing the force sensor with a displacement sensor, this way a position error is measured. It is interesting to see whether the results for replication error and repetition change. When they do, it means force and position tasks are perceived different.

*Persons with arm defect*

Although earlier research shows persons without arm defects give a reasonable indication for the results of persons with arm defects[10], it is suggested to do research for the perception of operating forces and cable displacements on both groups of participants. Previous research suggests good indications for the repetition but not for the reproducibility (= blind operating force – reference force) which can be compared to the replication error as the visual error was very small. More research into the possibility to use the results of persons without arm amputations as an indication for the results of persons with arm amputation is suggested.

## Conclusions

This study has given a first perspective on the perception of operating forces and cable displacements for shoulder harness controlled body powered prostheses. Operating forces and cable displacements should make good use of the proprioceptive feedback available, as this feedback has a low mental load. The purpose was to find the force-displacement combinations that could be reproduced best without visual feedback. The force error between a visual produced force and blind *re*produced force was a measure for the ability of a participant to control the operating forces and cable displacements with the shoulder harness.

- The perception of operating forces without visual feedback is best for operating forces between 24 to 32 N.
- The perception of cable displacements is dependent on the spring used; the larger the spring deformation, the better the force was reproduced.
- For higher operating forces and cable displacements it was more difficult to repeat the same force.

These results can be used as design criteria for improved prosthetic design.

## Recommendations

From the discussion it can be concluded there is still information missing for designing improved shoulder controlled prostheses. Follow up research is suggested to investigate:

- the operating forces and cable displacements for the upper boundaries of the research window;
- the thresholds for differences between force-displacement combinations when receiving position and force feedback information;
- the research areas with smaller and larger displacements and operating forces between 24 and 32 N for force tasks *and* position tasks
- the research areas with larger cable displacements where operating forces are lower than 24 N for force tasks *and* position tasks
- good perceived operating forces and cable displacements for persons with an arm defect;
- desired grasping forces and opening widths for ADL;
- whether the found errors have a large or minor effect when grasping and holding an object;
- the ability of humans coping with nonlinear transmissions in prosthetic design;
- fatigue and mental load for different force-displacement combinations;
- why underestimation of the force task is occurring and whether is also occurring for a position task.

Although more research on the topic is necessary, this research brings us one step closer to the force and displacement transmissions ratios needed for improved prosthesis design.

5627 words

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