# Moving towards two-way control

Ellen H.A. van Mil, Mona Hichert and Dick H. Plettenburg

*Delft Institute of Prosthetics and Orthotics, Delft University of Technology, Delft, The Netherlands*

## Abstract

An important advantage of body-powered prostheses, compared to other types of prostheses, is the presence of proprioceptive feedback. Proprioception makes it easier to perform goal directed movements. Body-powered prostheses (for transradial upper-limb amputees) used nowadays make use of one way control, which means that only the opening or the closing is controlled voluntary. By using one way control, proprioceptive feedback is only available for the movement that is controlled voluntary. To gain a broader feedback, it would be better to use two-way control. This means that the opening *and* the closing can be controlled voluntary. Two-way control can make the control of the prosthesis more natural and intuitive. To design such a prosthesis in the future, the inputs and the outputs must be known. The goal of this study is to investigate possible movements generating the inputs (operating forces and displacements) for a two-way controlled prosthesis.

The selection of suitable movements for control is done in two phases. First, the body parts useful for control in a cosmetically acceptable way are determined. Second, all movements produced by these body parts are analysed by using three criteria: 1. The control movement is no daily movement, 2. The movement can be performed in every posture needed to function normally in daily life, 3. The movement does not influence the position of the artificial hand. Only the movements fulfilling all criteria were considered suitable for control, resulting in the following movements: elevation of the shoulder, protraction of the shoulder, flexion of the trunk, rotation of the trunk and flexion of the toes.

Twenty subjects without arm defects (10 male/10 female, 25±2 years old) were requested to perform the five movements left and right. Per movement the maximum displacement and maximum forces at 0, 25, 50 & 75% of the maximum displacement were measured. Subjective perceptions of the participants regarding easiness, comfort and intuition were recorded in questionnaires.

For all movements, the operating force decreased with increasing displacement. The highest forces and displacements were found for shoulder elevation (left: 98.57±29.48N/80.5±22.6mm; right: 103.59±32.11N/85.5±19.9mm), whereas the lowest force and displacement values were found for toe flexion (left: 22.15±6.47N/17.5±5.0mm; right: 22.39±7.26N/17.5±5.0mm). All movements were easy and comfortable to perform. Flexion of the trunk was experienced less intuitive than other movements.

Of the five movements investigated, only shoulder protraction and elevation are considered suitable when using a Bowden cable. By designing a two-way system in the future, it is recommended to investigate the use of a wireless system. By using such a system, no hindering cables are necessary, which makes the prosthesis less elaborate and restricting. In the case of a wireless system, all investigated movements are suitable.

## Introduction

Body-powered (BP) prostheses use muscle power of the prosthesis user for operation of the terminal device[1]. Nowadays, one-way control is used for BP-prostheses for transradial upper-limb amputees. Two different one-way control systems exist: voluntary opening and voluntary closing. Voluntary opening means that the prehensor can be opened voluntary, while closing of the terminal device occurs involuntary by springs. Voluntary opening systems can be compared to a clothespin. In the case of voluntary closing control the opposite occurs, comparable to a pair of tweezers[2].

The main advantage of body-powered prostheses is the presence of proprioception. Since the prosthesis is driven by muscle action, sensory information in the muscles controlling the prosthesis makes the user aware of what the prosthesis is doing[3]. Proprioception is very important for goal-directed movements[4].

By using one-way control, proprioceptive feedback is only available about the movement that is controlled voluntary. To achieve a broader proprioception, it is desirable to have proprioceptive feedback about the opening *and* about the closing of the artificial hand. This can be achieved by using two-way control. Two-way control means that the opening as well as the closing of the artificial hand is performed voluntary, comparable to a scissors. Next to a broader proprioception, two-way control provides a more intuitive and natural way of prosthesis operation.

The inputs of a two-way controlled prosthesis are the operating forces and displacements produced by the body movements controlling the opening and the closing of the terminal device. These forces and displacements are transmitted to the terminal device, to result in the outputs of the system: grip force and opening width. The relations between the input forces and the output force are called the force transmission ratios. The displacement transmission ratios are the relations between the operating displacements and the opening width of the terminal device. The transmission ratios are dependent on the type of prosthesis used (transmission system and type of terminal device)[5, 6].

Up to now, only one system is known using two-way control. This system, shown in figure 1, was designed by Carnes in 1911[7]. It consists of three Bowden cables, attached to a harness. By performing glenohumeral flexion at the amputated side, the hand opens. By producing a pronounced dropping of the shoulder, the hand closes. The third cable was added to control a wrist lock. The system isn't used anymore nowadays, the reason for this is unknown. However, it seems that by dropping the shoulder, not only a tension occurs on the strap for closing, but also the strap for opening is stretched. This would mean that it is impossible to perform the control movements independently, resulting in a non-functioning two-way system.

To be able to design a better prosthesis using two-way control, the inputs and outputs of the system must be known. The outputs of the system are the pinch force and the opening width that are needed to perform all activities of daily living (ADL), which are approximately 34.3 N and 70 to 80 mm[8, 9]. But what are the inputs? In the one-way systems used nowadays, Bowden cables are used to transmit power. However, for two-way control, the type of transmission system that will be used is not yet determined. This means that it is unknown what operating forces (and displacements) are necessary for control. This gives the opportunity to first investigate the suitable movements to control a two-way system. Then, by defining the inputs (forces and displacements) these movements can produce, a useful two-way prosthesis can be designed.

The goal of this study is to investigate the operating forces and displacements that can be produced by movements suitable to control a two-way prosthesis for unilateral transradial amputees. This is done in two phases. First, the movements considered suitable for control of a two-way system will be defined. Second, the corresponding operating forces and displacements will be established. Finally, this will result in a database with suitable inputs, which can be used for future design of a two-way controlled prosthesis.

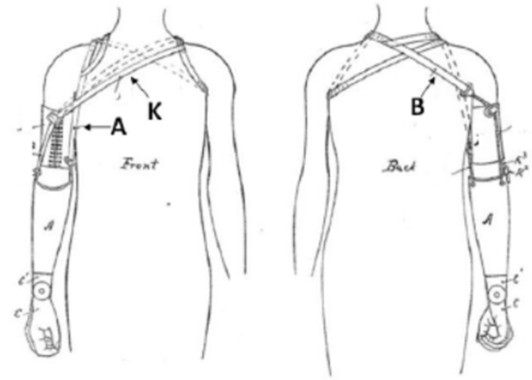



**Figure 1: Two-way body powered prosthesis designed by Carnes in 1911. Strap B is used for opening, which occurs while glenohumeral flexion of the arm at the amputated side takes place. To close the hand, strap A is put on tension by a pronounced dropping of the shoulder. Strap K is used for operation of the wrist lock[7].**

# Approach

## Selection movements

To formulate criteria to select suitable movements for prosthetic control, the three basic requirements for the design of prostheses were taken into account: control, comfort and cosmetics[10]. First, suitable body parts were selected. Then, a selection of suitable movements was performed.

*Selection of suitable body parts*

To select suitable body parts for prosthetic control, the following criterion was used:

- **Is it cosmetically acceptable to use the body part for prosthetic control?** To use a movement for control, it is necessary to place a certain device on the body part producing this movement (no matter what type of transmission system used, even in the case of a wireless system it is necessary to place for example electrodes on the body part). This criterion judges for every body part if it is cosmetically acceptable to place a device on the body part. It is considered acceptable if the device can be made invisible, for example by placing it underneath the clothes.

Due to this selection criterion, only the body parts face and neck were rejected.

*Selection of suitable movements*

For all body parts not rejected, the movements that can be produced by the joints of these parts were investigated (attachment A)[11]. All these movements were judged by using new selection criteria, all based on 'control':

- **1.The movement is no daily movement.** All movements needed to perform an activity of daily living are called 'daily movements'. No preliminary research is available describing 'daily movements'. Therefore, a list of daily movements was drawn up for this study. This was done by using the list of Activities of Daily Living (ADL). ADL are self-care tasks, which are necessary for fundamental functioning. The five most important ADL are dressing, eating, ambulating, toileting and hygiene[12]. Hygiene deals with activities as bathing and taking a shower, which occurs without wearing the prosthesis, so this activity is not taken into account. To define what movements are needed per activity, all activities were performed by the researcher and all movements needed were established (attachment B). For prosthetic control, it is important that the control movement is no daily movement to ensure that prosthetic control and daily activities do not hinder each other.

- **2.The movement is posture independent.** For an easy control it must be possible to perform the control movements in all postures performed most often in daily life. The postures regularly performed were defined by using the list of ADL. By performing every activity, the corresponding postures were established. This resulted in the following postures: sitting, standing, walking, stooping and reaching. This criterion focusses on the movements that are hindered while having the body in one of these postures. Again, no previous research could be used to define this. Therefore, the possibility to perform every movement in all regularly used postures was determined by the researcher. All movements that were difficult to perform in one of the postures were rejected by this criterion (appendix C.

- **3.The movement doesn't influence the position of the terminal device.** Some movements largely influence the position of the hand. This means that the object hold in the hand changes position when such a movement is performed, which results in necessary compensatory movements to get the hand or hook at the correct location. The need for compensatory movements is considered undesirable for prosthetic control, since it results in a less natural and more mentally challenging way of controlling. The movements resulting in a large change of the position of the terminal device were rejected by this criterion (movements in the shoulder joint and in the elbow joint).

Only the movements that fulfilled all three criteria were considered suitable, others were rejected (appendix D). This resulted in five suitable movements (see figure 2): elevation of the scapula (shoulder elevation), protraction in the sternoclavicular joint (shoulder protraction), lateral flexion of the spine (trunk flexion), lateral rotation of the spine (trunk rotation) and flexion of the toes. Since all five movements can be performed left and right, in total 10

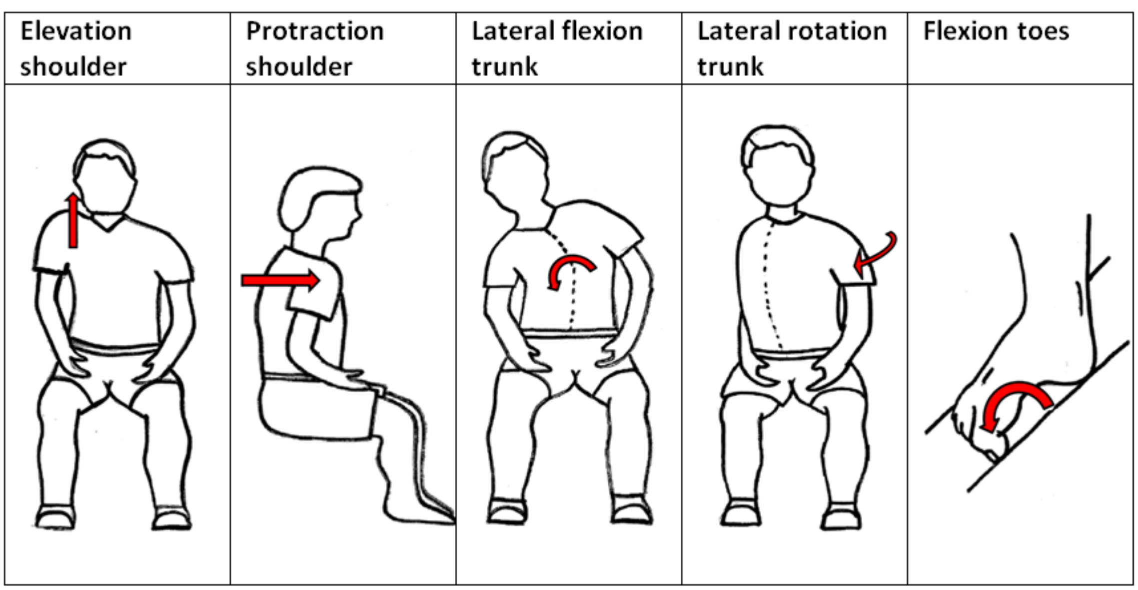



**Figure 2: The movements considered suitable for prosthetic control are elevation of the shoulder, protraction of the shoulder, lateral flexion of the trunk, lateral rotation of the trunk and flexion of the toes. All movements can be performed with the left and the right side of the body, resulting in 10 suitable movements.**

movements were considered suitable for prosthetic control.

## Define operating forces and displacements

In this study, the maximal operating displacement and maximal operating force will be established for all ten movements. But, these two inputs are not independent, since muscle force is dependent on muscle length[13]. The length of the muscles producing an operating force is related to the position of the joint, which is dependent on the displacement necessary to close the artificial hand. This displacement depends on the type of prosthesis used and the necessary opening width of the hand or hook. So, in the end, the operating force is dependent on the operating displacement.

To investigate operating force vs. operating displacement, it was chosen to measure the force at four different positions of the joint, namely at 0, 25, 50 and 75% of the maximal displacement that can be achieved by each movement. At 100% displacement, which is the maximal range of movement that can be achieved, the force is equal to zero. The division in parts of 25% was chosen, since the length measurements are performed on a centimetre-scale. By using this scale, the smallest possible division of the maximal displacement (without endangering the accuracy of the measurements) turned out to be in parts of 25%.

By measuring the forces and displacements the movements can produce, both variables were measured in the line of action of the movement, to make sure that the maximal values are determined.

# Method

## Participants

The sample population included 20 persons (10 men and 10 women) without an arm defect between the age of 20 and 30 years (mean age 25.3 $\pm$ 1.5 years). Three subjects were left-handed, all others right-handed. All participants were free of any kind of injury (neuro-muscular diseases, motor control disorders or sports injuries) to shoulders, back or feet. The subjects had a weight of 68.8 $\pm$ 8.8 kg and were 176.9 $\pm$ 8.9 cm tall. To see whether the subjects are a good sample of the population, some extra body characteristics were taken according to the measurement methods of Dined (width of shoulders (38.5 $\pm$ 3.6 cm), sitting height (94.4 $\pm$ 3.2 cm), waist circumference (79.4 $\pm$ 7.4 cm)). Each subject signed an informed consent before testing (appendix F). The local ethical committee approved the experiments.

## Apparatus

To measure the produced forces, a load cell (Feteris: FLLSB200 S-Beam junior, range 0 - 440 N) was used. The load cell was connected to a laptop via an amplifier system (Scaime: CPJ2S) and a data acquisition system (National Instruments: NI USB-6008). The force was measured with a sample frequency of 100 Hz. To view the produced forces on the laptop, LabVIEW (version 9.0.1) was used. In addition, a second laptop was used to make a video of the subject during the experiment. A schematic overview of the setup is shown in figure 3. For more technical details, see appendix G.

To measure the operating force and displacement produced by flexion and rotation of the trunk and by protraction and elevation, the subject wore a tight chest strap. To this strap an attachment strap was fastened. The subject was seated on a wooden board, to which different straps were attached. A measurement strap, with markings at every centimetre, was attached to one of these straps by a clasp. The load cell was placed in between the attachment strap and the measurement strap (see figure 3). The length of the measurement strap could be changed.

To measure the force and displacement produced by flexion of the toes, an iron socket was placed around the big toe. To this socket, the force sensor was attached. At the other side of the force sensor, the measurement strap (with markings) was connected. To attach this strap to the foot, it was lengthened by an 'ankle strap'. This 'ankle strap' was rotated around the ankle and fastened by a plier. To keep the measurement strap in contact with the skin at the dorsal side of the foot, an extra foot strap was placed around the fore foot (figure 3).

For every movement measured, the line of action of the load cell and the measurement strap was in line with the line of action of the movement. This resulted in four different ways of applying the equipment to the subject (appendix I).

## Procedure

All subjects performed the ten different movements. The sequence of the movements was randomized for every subject. The subject was seated on the wooden board and was asked to sit up straight by placing the arms relaxed on the upper legs. All subjects wore an undershirt or shirt.

For every movement, the maximal displacement that could be achieved was determined. This was done by using the measurement strap, which was free to move during this measurement. While the subject tried to reach maximal range of movement, the distance between the force sensor and the board (or between the force sensor and the strap around the fore foot) increased, resulting in a lengthening of the mea-

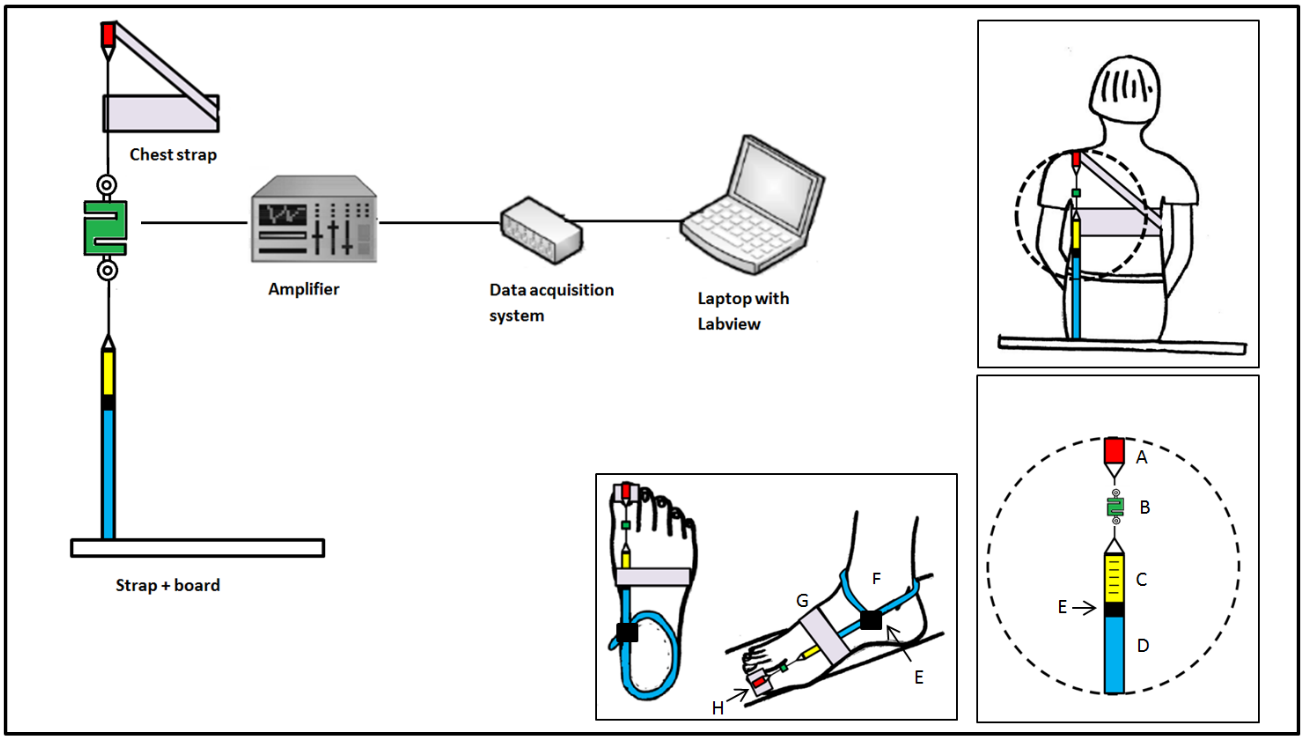



**Figure 3: Schematic overview of measurement equipment setup (the extra laptop used to film the subject is not shown). In the boxes the objects used to connect the force sensor to the subject are shown (A: attachment strap, B: load cell, C: measurement strap, D: strap attached to wooden board, E: clasp, F: strap around ankle, G: foot strap, H: iron socket around toe).**

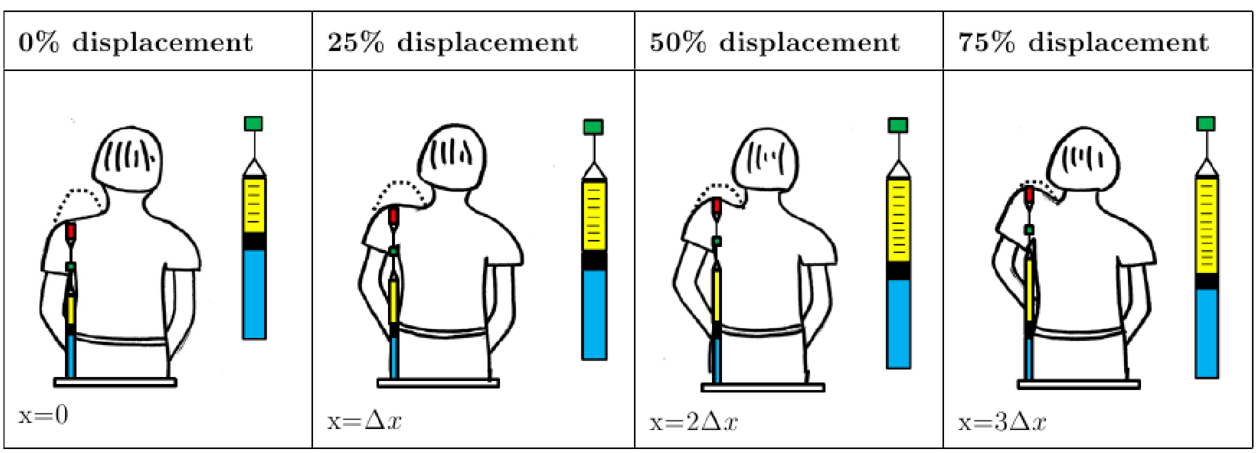



**Figure 4: Measuring force vs. displacement. This figure shows how the elevation force is measured at 0, 25, 50 and 75% of maximal elevation displacement. Maximal elevation is shown by the dotted line. The length of the measurement strap restricts the amount of elevation possible. By increasing the length with $\Delta x$, the amount of elevation possible increases with 25% of maximal displacement.**

surement strap. By using the markings on the measurement strap, the length increase (which is equal to the maximal displacement) was measured. Then, the maximal displacement measured was divided in quarters, resulting in the values corresponding to 25, 50 and 75% of the maximal displacement.

Following, the force is measured at these four different operating displacements (see figure 4). The length of the measurement strap defined the amount of movement possible. To measure the force at 0% displacement, the distance between the load cell and the wooden board was set as small as possible. This was done by setting the length of the measurement strap at the smallest length possible without exerting a force on the load cell. To make sure that the distance between the board and the load cell could not increase due to sliding, the measurement strap was fixed by using a locking plier. Then, the subject was asked to exert the highest force possible and hold this force until the researcher gave permission to stop. Stopping exerting force was allowed when the produced force had reached a plateau for approximately 2 seconds. The force measured was visualized on the laptop, which was only visible for the researcher. After performing the force measurement three times, the length of the measurement strap was lengthened with 25% of the maximal displacement and fixed at that position. This gave the subject the ability to move up to 25% of maximal displacement. Again, the subject produced the highest force as possible. After performing all three measurements at 25% displacement, the same steps were repeated for 50 and 75% of maximal displacement. In the end, 12 force measurements were performed per movement. The operating force produced by flexion of the toes was only measured at 0% and 50% displacement. This is because the operating displacement was too small to measure the force accurately at every quarter of maximal displacement.

For every subject, the same instructions were given how to perform the movements (appendix I). For all movements it was very important that solely the requested movement was performed, so no other accompanying movements were allowed. By filming the subject during the experiment, the researcher was able to notice erroneous performances. If the movement was not performed correctly, the force measurement was redone.

After finishing all twelve force measurements for one movement, the subject filled in a questionnaire to define how performing the movement was experienced. The questionnaire consisted of three statements:
1. The movement was easy to perform,
2. I had to think how to perform the movement,
3. Performing the movement felt uncomfortable.

Each statement could be judged by choosing one of the following options: strongly agree, tend to agree, neither agree nor disagree, tend to disagree or strongly disagree. In addition, it was asked if it hurt to perform the movement. If some pain was experienced, the subject was asked to colour the region where the pain was felt by using a body map.

## Data analysis

All calculations were performed by using MATLAB R2011b. SPSS 16.0 was used to execute all statistical tests, with a significance level of $p<0.05$.

*Operating displacement and forces*

For every movement, the force was measured at 0, 25, 50 and 75% displacement. At every displacement, three repetitions were performed. To remove possible sensor artefacts of the load cell, the raw data of each repetition was filtered by calculating the mean of ten consecutive data points and assigning this mean value to all ten data points. Figure 5 shows a characteristic example of the filtered raw data of three repetitions for one subject.

To calculate the maximal force at 0% displacement per subject, the maximal value of each of the three repetitions was calculated, resulting in three maximal values. Then the average of these three values was taken. This resulted in the mean force produced at 0% displacement for one subject. The same was done to calculate the mean forces per subject at 25, 50 and 75% displacement, resulting in four mean forces per subject per movement. Finally, the forces per displacement of all subjects were averaged. This resulted in four mean maximal forces, belonging to 0% displacement (force 1), 25% displacement (force 2), 50% displacement (force 3) and 75% displacement (force 4). Additionally, the standard deviations over all subjects per force at each displacement were calculated.

All these calculations are performed for every movement, resulting in four mean (maximal) forces per movement. The mean operating *displacement* per movement was defined by calculating the average (and standard deviation) over all subjects.

*Statistics*

To investigate significant left-right differences, paired T-tests were performed. Independent T-tests were performed to establish significant gender differences. In addition, influences of subject characteristics (weight, height, width of the shoulders, sitting height and waist circumference) on the produced maximal forces and displacements were investigated by calculating the Pearson correlation coefficients. This was done by focussing on the forces at 0% displacement.

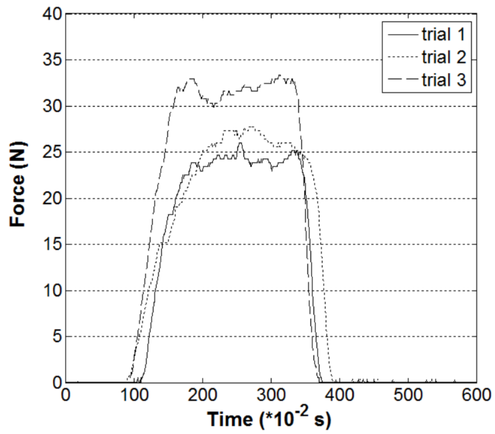



**Figure 5: Characteristic example of the filtered raw data. Each subject performed three repetitions per force measurement.**

*Work*

By using the measured operating forces and displacements, the maximal amount of work that can be produced by each movement can be calculated. The amount of work is useful information when designing a new prosthesis. To calculate the amount of work produced by each subject for every movement, the operating forces were integrated along the displacement path. This was done in four steps. First, the work produced when the operating displacement is equal to 25% of maximal displacement was calculated by using the following formula:

$$W = \int_{x=0}^{x=25\%} F(x)dx$$

Where W = work in Nmm, F(x) is the operating force in N and x=25% is the displacement in mm that corresponds to 25% of maximal displacement. In steps 2-4, the work was calculated similarly, but the upper limit of the integral was changed to the displacement (in mm) that corresponds to 50, 75 and 100% respectively. Performing all four steps for every subject resulted in the amount of work at each quarter of maximal displacement per subject. Finally, to calculate the average work over all subjects, the work per displacement was averaged over all subjects.

*Subjective perceptions*

The answers to the statements of the questionnaires were labelled with scores from 1 to 5, where a score of 5 was assigned to the most positive answer and a score of 1 to the most negative answer. This means that for the statement: 'The movement was easy to perform', the answer 'strongly agree' was scored with a 5 and the answer 'strongly disagree' was scored with a 1. For the two other statements, the answer 'strongly agree' was assigned the score 1 and 'strongly disagree' the score 5. After scoring the answers of all subjects, the mean score per statement per movement was calculated.

# Results

The mean operating displacements and forces for every movement are shown in figure 6 and 7 and in table 1. In addition, the line of action of each movement and the main muscles involved to perform the movements are shown in the table.

*Operating displacements*

The largest operating displacement was achieved by performing elevation of the shoulder (left: 80.5 ± 22.6 mm and right: 85.5 ± 19.9 mm). The smallest operating displacement occurred with flexion of the toes, both at the left and the right side a mean displacement of 17.5 ± 5.0 mm was achieved. No significant left-right differences were found for all movements.

*Operating forces*

For all movements, the highest force was measured at 0% displacement. In addition, the operating force decreased with increasing displacement. By performing elevation of the shoulder the highest forces were achieved (left: 98.57 ± 29.48 N, right: 103.59 ± 32.11 N, at 0% displacement). The lowest forces resulted from flexion of the toes (left: 22.15 ± 6.47 N, right: 22.39 ± 7.26 N, at 0% displacement). Three significant differences were found in the forces produced left and right. At 0% displacement, the operating force of protraction with the right shoulder was higher than with the left shoulder ($p = 0.006$). By rotation of the trunk to the right, the force produced at 0% and 25% of maximal displacement was significantly higher than by rotation to the left ($p = 0.006$ resp. $p = 0.010$).

*Body dimensions*

Overall, the participants are a good reflection of the mean population. However, the subjects of this study have a lower weight, smaller width of the shoulders and a larger sitting height. Some of these distinctive body dimensions are correlated to the maximal forces (at 0% displacement) and displacements measured. The weight is correlated to the force produced by rotation of the trunk (left: $r = 0.494$, $p = 0.027$, right: $r = 0.486$, $p = 0.03$). A lower weight resulted in lower forces. In addition, the width of the shoulders is positively correlated to the operating displacement of protraction by the left shoulder ($r = 0.500$, $p = 0.025$).

No significant gender differences were found in the operating forces and displacements.

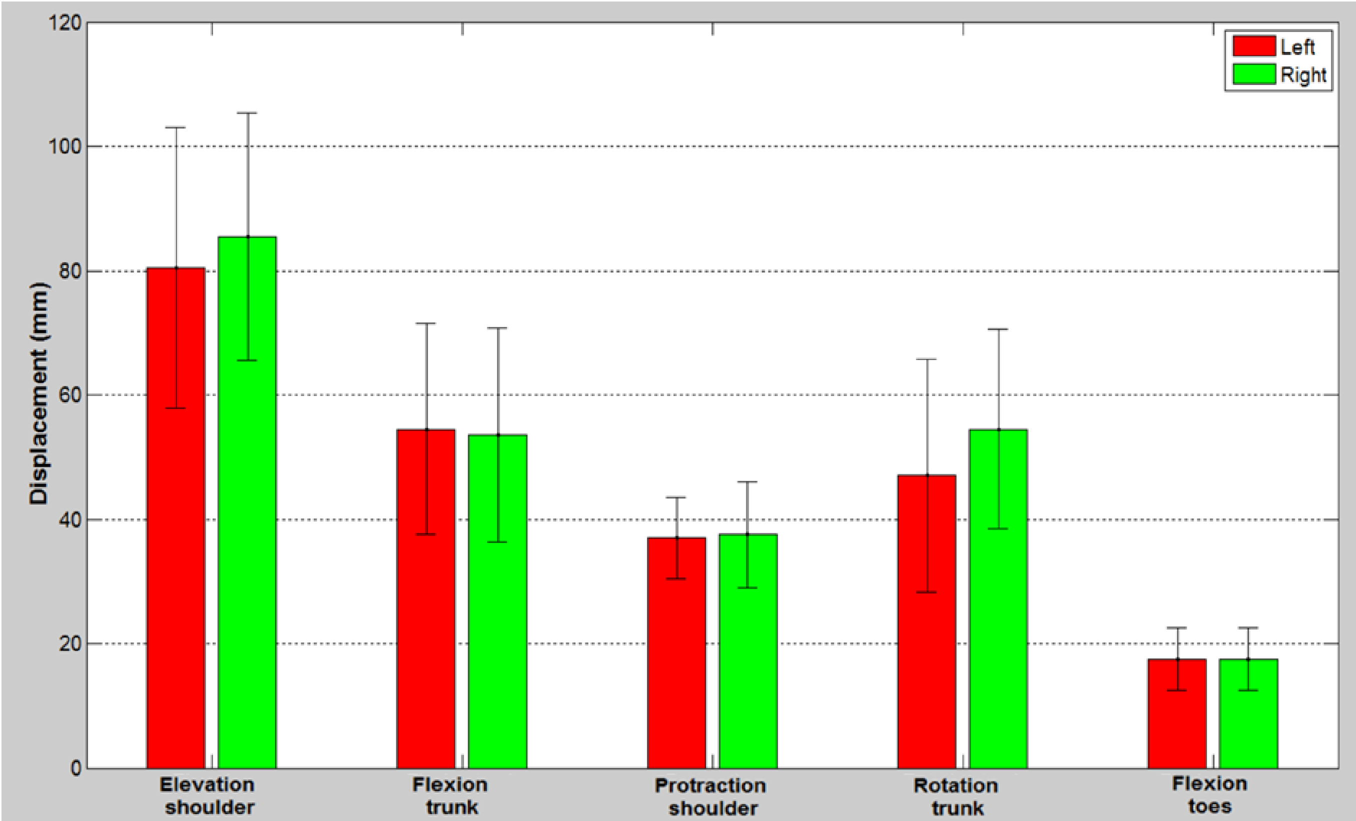



**Figure 6: Average operating displacement per movement. Error bars indicate standard deviations over all subjects. No significant differences were found between the displacements produced left and right.**

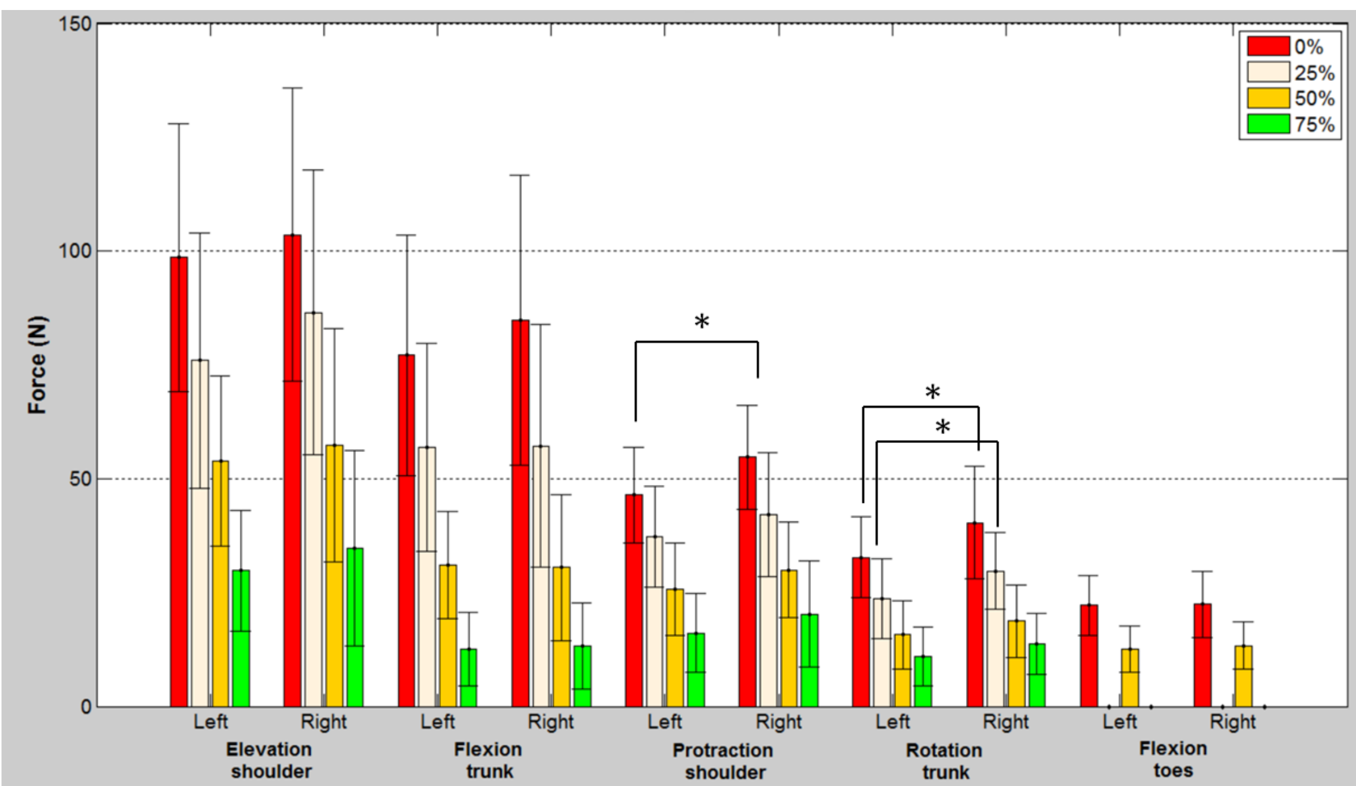
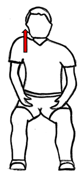
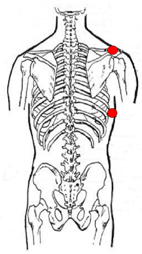
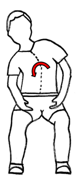
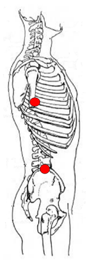
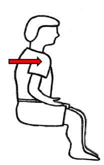
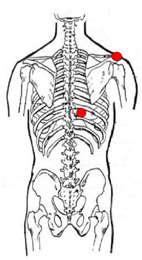
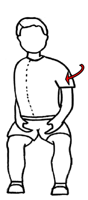
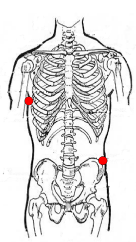



**Figure 7: Average operating force per movement. Error bars indicate standard deviations over all subjects. A star indicates a significant difference between the force produced left and right.**

**Table 1: Characteristics of all movements investigated, ordered on decreasing operating force. The virtual line between the two landmarks indicates the line of action. Values are mean (standard deviation) over all subjects. F1 - F4 are the mean forces measured at 0%, 25%, 50% and 75% displacement respectively.**

| **Movement** | **Landmarks** | **Main muscles involved** | | **Displ. (mm)** | **F1 (N) -0%-** | **F2 (N) -25%-** | **F3 (N) -50%-** | **F4 (N) -75%-** |
|---|---|---|---|---|---|---|---|---|
| Elevation  |  | -M. trapezius, pars descendens<br>-M. levator scapulae<br>-M. rhomboideus minor<br>-M. rhomboideus major | Left | 80.5 (22.6) | 98.57 (28.48) | 75.95 (28.04) | 53.95 (18.72) | 29.77 (13.19) |
| | | | Right | 85.5 (19.9) | 103.59 (32.11) | 86.53 (31.37) | 57.30 (25.64) | 34.83 (21.46) |
| Flexion trunk  |  | -M. quadratus lumborum<br>-M. psoas major<br>-M. obliquus externus abdominis<br>-M. obliquus internus abdominis | Left | 54.5 (17.0) | 77.11 (26.35) | 56.89 (22.94) | 30.99 (11.78) | 12.50 (8.07) |
| | | | Right | 53.5 (17.3) | 84.81 (31.90) | 57.20 (26.74) | 30.52 (16.05) | 13.27 (9.53) |
| Protraction  |  | -M. serratus anterior<br>-M. pectoralis minor | Left | 37.0 (6.60) | 46.41 (10.54) | 37.27 (11.05) | 25.67 (10.20) | 16.11 (8.71) |
| | | | Right | 37.5 (8.5) | 57.74 (11.46) | 42.14 (13.54) | 29.95 (10.56) | 20.29 (11.66) |
| Rotation trunk  |  | -M. transversus abdominis<br>-M. obliquus externus abdominis<br>-M. obliquus internus abdominis | Left | 47.0 (18.7) | 32.73 (8.84) | 23.72 (8.81) | 15.72 (7.43) | 10.88 (6.48) |
| | | | Right | 54.5 (16.1) | 40.36 (12.36) | 29.75 (8.34) | 18.77 (7.94) | 13.72 (6.77) |
| Flexion toes  |  | -M. flexor hallucis brevis<br>-M. flexor hallucis longus<br>-M. flexor digitorum brevis<br>-M. flexor digitorum longus<br>-Mm. lumbricales | Left | 17.5 (5.0) | 22.15 (6.47) | - | 12.67 (5.10) | - |
| | | | Right | 17.5 (5.0) | 22.39 (7.26) | - | 13.34 (5.25) | - |

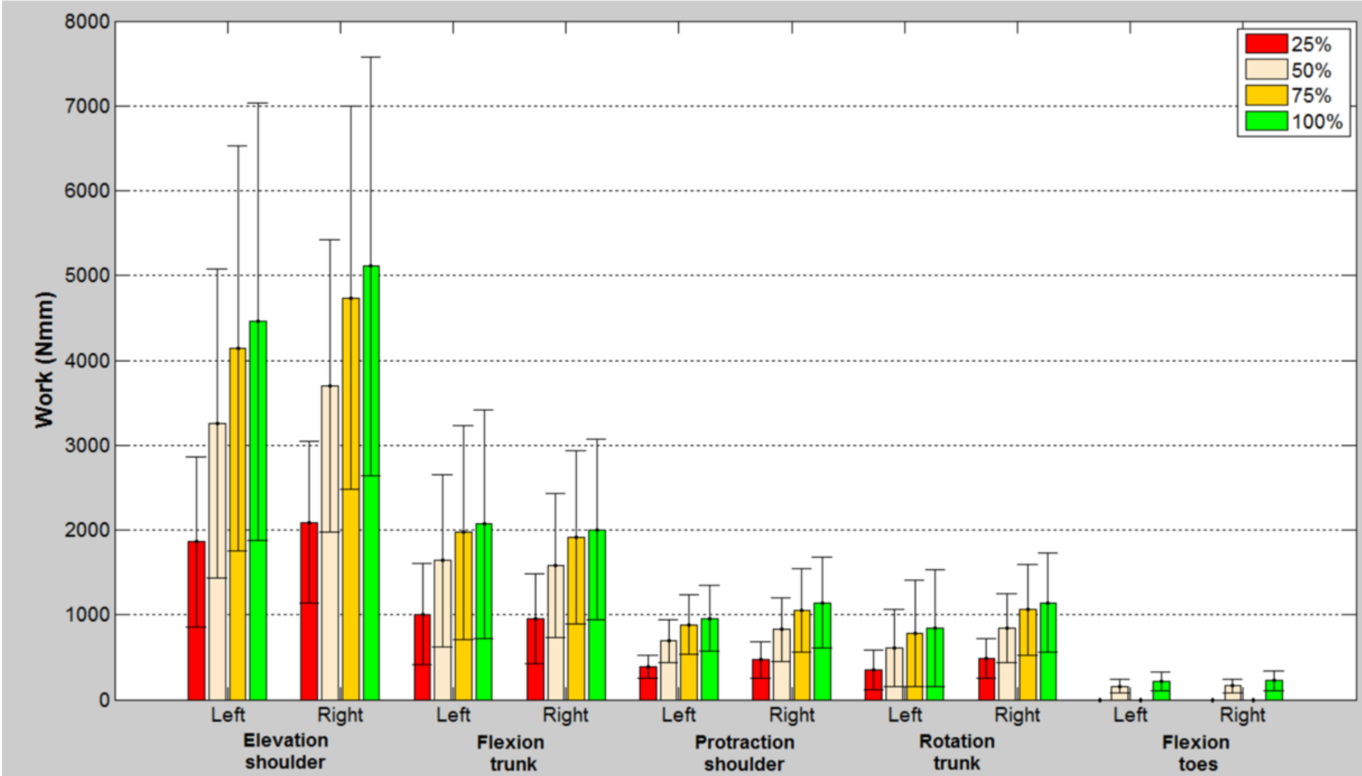



**Figure 8:** Average work per operating displacement per movement. Error bars indicate standard deviations over all subjects.

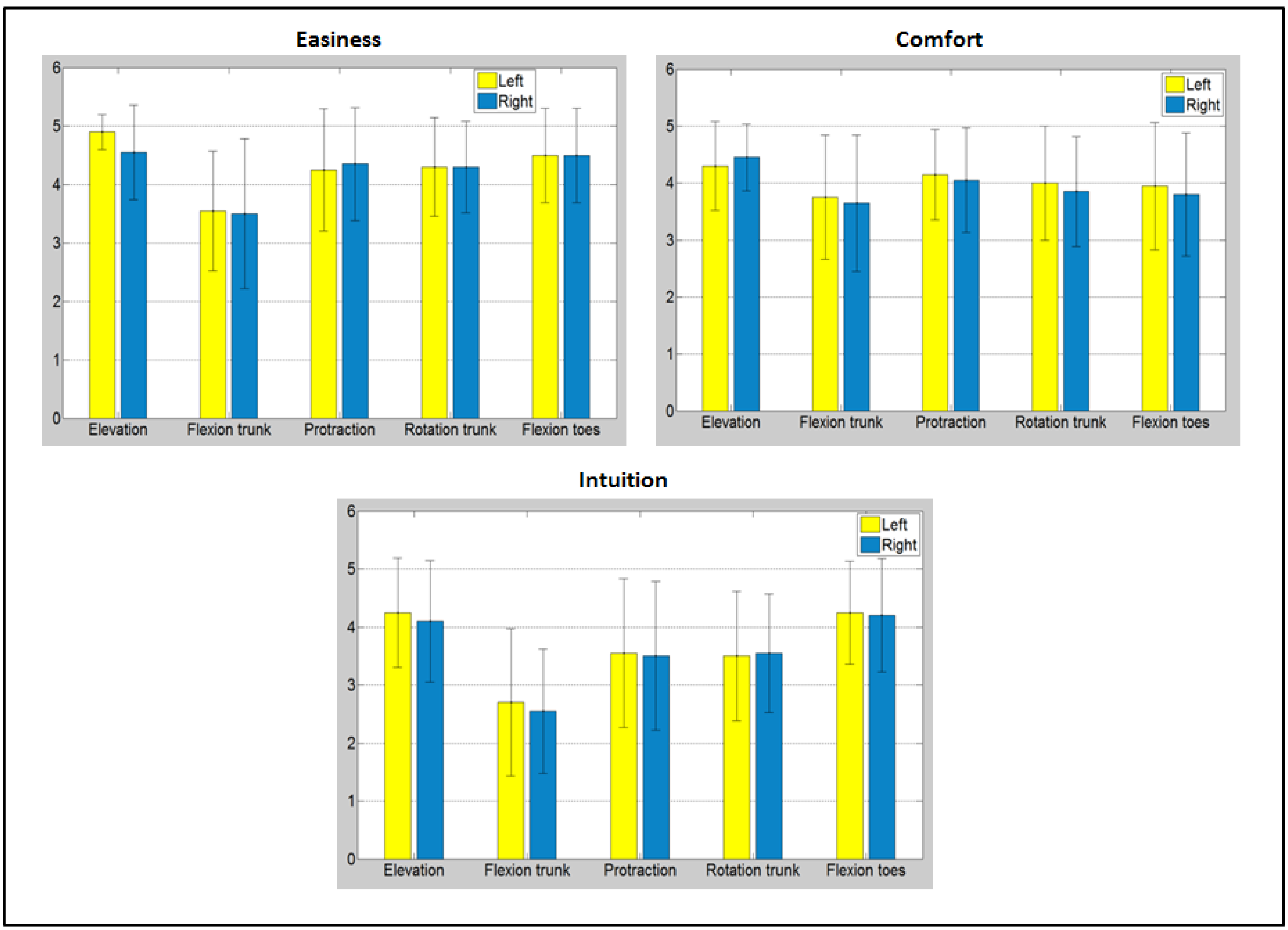



**Figure 9:** Results of the questionnaires filled in after performing each movement. Score 5 = positive, score 1 = negative. Error bars indicate standard deviations over all subjects.

*Work*

The highest maximal work was achieved by performing elevation (left: 4455.7 ± 2583.6 Nmm, right: 5108.6 ± 2467.8 Nmm). Flexion of the toes resulted in the lowest work (left: 217.6 ± 113.3, right: 222.4 ± 112.2).

*Subjective perceptions*

The results of the questionnaires are shown in figure 9. The answers were scaled from 1 to 5, the higher the score, the easier, comfortable or intuitive performing the movement was experienced. For all movements, the easiness score is larger than 3, indicating that all movements were easy to perform. Also the comfort score is larger than 3 for all movements, meaning that the participants didn't experience any discomfort while performing. Not all movements were considered intuitive. Rotation of the trunk (left and right) scored a mean score of less than 3, which means that on average, the participants had to think how to perform the movement. The body map is never used, indicating that the subjects experienced no pain while performing the movements.

# Discussion

The goal of this study was to investigate possible movements generating the input (operating forces and displacements) for a two-way controlled upper-limb prosthesis. After performing a strict selection process, where movement freedom and cosmetics played an important role, the following movements were considered suitable for prosthetic control: flexion of the trunk, rotation of the trunk, elevation of the shoulder, protraction of the shoulder and flexion of the toes. All movements can be performed left and right, resulting in 10 different movements. The operating forces and operating displacements of these movements are defined. Additionally, the subjective experience while performing the movements is established. The results of this study can be used for future design and research of a two-way controlled body-powered prosthesis.

For all movements, the operating force reduced with increasing operating displacement. Elevation of the shoulder (left and right) resulted in the highest operating displacements and forces. Flexion of the toes resulted in the lowest values.

All movements investigated were considered easy and comfortable to perform. Flexion of the trunk is considered less intuitive than other movements investigated. So, when using this movement for prosthetic control, more training may be required to make performing the movement more natural.

## Previous research

The possibility to compare the present results with previous research is limited. Only Taylor[14] and Bertels[15] investigated maximal operation forces and displacements as well. The results of Taylor's study are not useful for comparison, since other movements are investigated in this study. The elevation force and displacement measured in Bertels study (125 N and 130 mm) are comparable to the values measured in this study (left: 98.57 N and 80.5 mm, right: 103.59 N and 85.5 mm).

The operating force and displacement measured by Bertels for protraction (scapular abduction, 160 N and 80 mm) differ to the present study (left: 46.41 N and 37.0 mm, right: 57.74 N and 37.5 mm). This may be due to the fact that only one subject was studied by Bertels. Also, the instruction given how to perform the movement may have influenced the values. When performing protraction, the upper body tends to rotate as well. In the present study, this rotation was not allowed. Allowing this rotation by Bertels may have resulted in a higher operating force.

## Body dimensions

The participants in the study had a lower weight, smaller shoulder width and larger sitting height than the mean population. The shoulder width is correlated to the amount of displacement produced by protraction of the left shoulder. The force produced by rotation of the trunk in both directions is correlated to the weight of the subject. This means that the operating displacement measured for protraction (left) and the rotation forces measured might be lower for the subject group investigated in this study compared to the mean population.

## Two-way control by Bowden cables

Body-powered upper limb prostheses used nowadays consist of a Bowden cable attached to a figure-of-nine harness at one end and to a terminal device at the other end. By performing glenohumeral flexion in the shoulder, protraction or a combination of both, the Bowden cable is tensioned, resulting in a motion of the terminal device. How does using this Bowden-cable system for two-way control look like?

*Bowden cable*

The main disadvantage of Bowden cables is the presence of high friction forces. Due to this friction, the path of the cable is important. To keep friction forces as low as possible, the path should be as straight as possible[16], which means that the body parts producing the control movements must be as close as possible to the artificial hand. Of the ten movements investigated, only protraction and elevation of the shoulder are considered suitable when using a Bowden cable.

Controlling opening and closing of the prehensor by Bowden cables can be done in two different ways. The first option is to use both shoulders for control, which means that one shoulder is used to control the opening and the other to control the closing. This can be done by performing the same movement at both shoulders (elevation or protraction) or by performing elevation at one shoulder and protraction at the other. An advantage of using two shoulders for control is that a clear distinction is present between the two control movements. Additionally, different muscles are used for both movements, resulting in less fatiguing of the muscles. A disadvantage of using two shoulders is that two Bowden cables are needed: one coupling the movement of the left shoulder with the terminal device and the other to couple the right shoulder. Using two Bowden cables results in the need for a more elaborate system, which can result in discomfort and hindering by the cables of the performance of daily activities. Another disadvantage is that both shoulders loose a degree of motion freedom.

The second option is using only one Bowden cable for control. Using one cable means that the same movement (elevation, protraction or a combination of both) is used for the closing and for the opening of the terminal device. By using one shoulder for control, it is recommended to use the shoulder at the amputated side, since this means a small path of the Bowden cable, resulting in the lowest friction forces. An advantage of using one cable for control is that the harness is simpler and probably more comfortable. However, by using one control movement, a locking mechanism and a switch are required. It is recommended to use an automatic lock and switch. This means that the hook or hand locks automatically when the hand is closed. When performing the control movement again, the prehensor unlocks automatically and the produced force and displacement are used to control the opening motion. A disadvantage of using one shoulder for control is that the same muscles are used for opening and closing, which may result in muscle fatigue or even muscle overloading. More research is needed to investigate which option (one or two shoulders) is the most user-friendly method for control of a two-way system.

*Harness*

The Bowden cable(s) must be attached to a harness. The figure-of-nine harness used nowadays is suitable for control by protraction, which means that no new harness needs to be designed when using this movement for control. In contrast, for control by elevation the design of a new harness is needed.

*Terminal device*

Up-to-now, no terminal device exists that is suitable for two-way control. By designing this device in the future, the mechanical properties should be fine-tuned to the operating forces, displacements and work that can be achieved by elevation or protraction of the shoulder.

## Alternative systems

Using a Bowden cable for power transmission has the disadvantage that high friction forces arise. This results in the need for high operating forces. In addition, only movements produced by body parts close to the artificial hand are usable for control. For the future, it is recommended to investigate other power transmission systems for two-way control of body-powered prostheses.

*Powered cable steering*

A solution to the problem with high operating forces due to the use of Bowden cables is powered cable steering[17]. This system is comparable to the system used for powered steering of a car. By using such a system, the required operating forces and displacements are lower while the same outputs are achieved.

Powered steering can be established in several ways. One of the options is to use hydraulics. Dependent on the type of hydraulic cylinder used, the transmission ratio can be set. By using hydraulics instead of a Bowden cable less friction occurs, so the system is more efficient [18].

Another option is to use a servo mechanism. With this mechanism, mechanical energy produced by body movements is transmitted into electric energy to operate a motor. Here also, the transmission ratio can be set by adjusting the relation between the amount of motor energy and mechanical energy. An advantage of using a motor instead of a hydraulic cylinder is that the transmission ratio can be set more easily to the needs of the individual, which is desirable since the variation in the produced operating forces and displacements between subjects is large. On the other hand, using a motor requires powering of the system. In addition, adding a motor results in a heavier system.

By using powered steering the presence of proprioception is maintained, since the prosthesis is still (partly) body powered, so feedback about the amount of force and displacement is available. However, there is no direct coupling anymore, which may result in more training time to learn the new transmission ratios.

*Wireless*

A disadvantage of the present system and the powered cable steering systems is that in all cases cables are necessary for the transmission of power. This results in the need for control movements produced by body parts close to the amputated arm (shoulder movements), to minimalize hindrance of the cables. This problem can be solved by creating a wireless system. Such a wireless system contains of two 'parts' that can be attached to the body. In between these parts two sensors are placed. One sensor is able to measure force, the other to measure displacement. The sensors are connected to the parts attached to the body by a cable. The line of action of this cable must be similar to the line of action of the control movement. An actuator is placed on the terminal device. By performing the control movement the cable is tensioned and the sensors measure the amount of force and displacement. This information is send to the actuator. Finally, the terminal device is actuated (opened or closed). The amount of grip force and the opening width depend on how the transmission ratios are set.

Since the system is still partly cable-controlled, proprioceptive feedback is available. An advantage of using a wireless system is that, in contrast to the system using Bowden cables, all movements investigated in this study are suitable for control. A disadvantage of a wireless system is that an actuator is needed, which must be powered.

## Future research movements

The results of this study give an overview of the forces, displacements and work that can be produced by the ten movements considered suitable for control. More research is necessary to investigate other characteristics of these movements.

To ensure an accurate operating of the artificial hand or hook, the movements used for closing and opening must give good proprioceptive feedback. Plettenburg and Hichert (2011) and Valk et al. (2012) investigated for which operating forces good proprioceptive feedback is available[19, 20]. By doing this, they focussed on controlling a shoulder harness by performing shoulder movements. For these movements, an operating force between 24 and 32 N resulted in the best proprioceptive feedback. It is recommended to investigate the same for the ten movements of this study. By knowing the operating forces resulting in the best proprioceptive feedback, the most optimal transmission ratios can be calculated, which can be used for the design of the prosthesis.

In addition, the force and displacement sensitivities for all movements must be established. This means that the minimal amounts of operating forces and displacements that can be distinguished by the user are investigated. If only large force differences are felt by the user and the maximal force of the movement is low, it is difficult to control the grip force precisely. The same holds for the control of the opening width; the minimal distinguishable operating displacement must be small enough to result in accurate control.

To provide a good control, it is important for the user to be able to have a good control of the amount of force produced. In this study, it is only taken into account if a force production is possible during activities of daily living, it is not investigated if it was also possible to control the amount of force produced during these activities. For future research it is recommended to investigate the possibility to control the amount of force for each of the ten movements during the performence of ADL.

Finally, the forces measured in this study are maximal forces. Using maximal forces for operation is not recommended, since this would result in fast fatiguing of the muscles. A muscle is able to produce 18% of the maximal force continuously without getting fatigued[21]. However, in the case of controlling a prosthesis, it may not always be necessary to constantly produce force (for example when locking mechanisms are used), making it possible to use a higher percentage of the maximal force. More research is needed to define what percentage of the maximal force can be used for prosthetic control, without getting fatigued.

## One-way control

Although the focus of this study is control of a two-way system, it is also useful to check if the movements studied, which are different than the movements used for control nowadays, could be used in combination with a one-way body-powered system available nowadays. By using the results of Smit et al. [5, 6] it can be analysed if the inputs produced by the movements are suitable for one-way control without redesigning the transmission system or terminal device. Since only the movements of the shoulder (elevation and protraction) are considered suitable for operating a Bowden cable, only these movements will be analysed.

According to Smit et al. (2012), the most optimal voluntary opening hook is the Hosmer 5XA hook with three bands[6]. To control this hook, an operating force of 95 N and an operating displacement of 46 mm are necessary to fully open the hook. In addition, a work of 3206 Nmm is needed. The best hand was the Hosmer Sierra hand, fully opened with 25 mm displacement, a force of 75 N and a work of 1152 Nmm. By comparing the results in table 1 and figure 8 to these values, it can be concluded that both elevation and protraction are not suitable to control the hook, since both movements cannot produce a force of 95N at 46mm displacement. To control the hand, only elevation is suitable.

The voluntary closing hook requiring the lowest activation force is the TRS hook, which needs a cable force of 33N, a cable excursion of 49 mm and a work of 242 Nmm to produce a pinch force of 15N[5]. Considering these values, only elevation at the left and right side is suitable to operate this hook. The inputs necessary to control the hand with the lowest activation force (Hosmer APRL hand) are 61N, 37mm and 831 Nmm. Again, only elevation at both sides is able to produce these inputs to control the hand.

It can be concluded that only elevation is suitable for one-way control by using a Bowden cable and commercially available hooks or hands. It is useful to investigate the option to design a new harness to use elevation for control, since using this movement results in more movement freedom for the user than the movements used nowadays. However, in the case of the Hosmer 5XA hook and the Hosmer Sierra hand fatigue can be a problem, since almost the maximal force is needed for control.

### Study limitations

The participants studied were all aged between 20 and 30 years and were all sportive. More research is necessary to determine the forces and displacements that can be produced by other sample groups. In addition, all subjects were non-disabled. For future design of a two-way controlled prosthesis it is necessary to investigate the force and displacement differences between disabled and non-disabled subjects.

Another limitation of this study is the choice to measure all forces in sitting posture. This was done to minimalize the possibility to perform other movements than intended during the experiment. Measuring in standing posture may have resulted in other forces and displacements.

Finally, since no research was available about what movements are difficult to perform in each posture and what movements are needed for each activity of daily living, some speculations were needed to make it possible to analyse what movements are suitable for control. This may have resulted in the rejection of movements that may also be suitable for control. However, the method to define the operating forces and displacements used in this study is usable for all movements. So, if future research concludes that other movements than the ten movements investigated in this study are also useful control movements, the operating forces and displacements of these movements can also be measured by using the measuring method of this study.

### Conclusions

The goal of this study was to investigate possible movements generating the inputs for a two-way controlled prosthesis. Five movements were considered suitable for control: shoulder elevation, shoulder protraction, trunk flexion, trunk rotation and toe flexion. For these movements operating forces and operating displacements were defined. Shoulder elevation resulted in the highest, toe flexion in the lowest forces and displacements.

Of the five movements investigated, only shoulder protraction and elevation are considered suitable when using a Bowden cable. By designing a two-way system in the future, it is recommended to investigate the use of a wireless system. By using such a system, no hindering cables are necessary, which makes the prosthesis less elaborate and restricting. In addition, all investigated movements are suitable for control when using such a system.

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# Moving towards two way control - Appendices

Ellen H.A. van Mil, Mona Hichert and Dick H. Plettenburg

*Delft Institute of Prosthetics and Orthotics, Delft University of Technology, Delft, The Netherlands*

## Contents

# A Movements per joint

In the table, all movements that can be performed by each joint are shown. The joints at the scapula and clavicle are taken together, just like the elbow and the radioulnar joint.

| |
|---|
| **Hip** |
| Flexion |
| Extension |
| Adduction |
| Abduction |
| Endorotation |
| Exorotation |
| **Knee** |
| Flexion |
| Extension |
| Rotation inwards |
| Rotation outwards |
| **Toe joints** |
| Flexion |
| Extension |
| **Ankle** |
| Flexion |
| Extension |
| Inversion |
| Eversion |
| **Shoulder** |
| Exorotation |
| Endorotation |
| Adduction |
| Abduction |
| Anteversion |
| Retroversion |
| **Elbow and radioulnar joint** |
| Flexion |
| Extension |
| Supination |
| Pronation |
| **Scapula and clavicle** |
| Depression |
| Elevation |
| Protraction |
| Retraction |
| **Spine** |
| Ventral flexion |
| Dorsal extension |
| Lateral flexion |
| Lateral rotation |

# B Activities of Daily Living

To define what movements are necessary to perform the activities of daily living, every activity was performed. While performing the activity, every movement of every joint was analysed: is it necessary to perform this movement or not? An example is the activity ambulating, which includes i.e. walking and cycling. For walking, it was necessary to flex and extend the knee and hip. In addition, the ankle performed dorsal and planar flexion and the toes were extended. All other movements in these joints or in other joints were not necessary for walking. For cycling, the same movements in hip, knee and ankle were necessary. To hold the bicycle handlebar, anteversion in the shoulder was also needed.

Another example is the analysis which movements are needed for dressing. All movements that were needed to fully dress yourselves (socks, underwear, shirt, pants and shoes) were written down. This resulted in the movements shown in the table below.

| **ADL** | **Body part involved** | **Movements involved** |
|---|---|---|
| Ambulating | Hip | Flexion<br>Extension |
| | Knee | Flexion<br>Extension |
| | Shoulder | Anteversion |
| | Ankle | Flexion<br>Extension |
| | Toe joints | Extension |
| Dressing | Hip | Flexion<br>Extension |
| | Knee | Flexion<br>Extension |
| | Shoulder | Anteversion<br>Abduction |
| | Elbow and radioulnar joint | Flexion<br>Extension<br>Pronation<br>Supination |
| | Ankle | Flexion<br>Extension |
| | Spine | Ventral flexion |
| Eating | Elbow and radioulnar joint | Flexion<br>Pronation<br>Supination |
| Toileting | Hip | Flexion<br>Extension |
| | Shoulder | Anteversion<br>Retroversion<br>Abduction<br>Adduction |
| | Elbow and radioulnar joint | Flexion<br>Extension<br>Pronation<br>Supination |
| | Spine | Ventral flexion<br>Dorsal extension |

## C Posture dependence movements

To analyse what movements cannot be performed freely in every posture, it was tried to perform all movements of every joint in every posture. A movement was considered hindered by the posture in two cases:
1. The movement was hard to perform or impossible to perform in the posture.
Example: Performing depression or retraction is hard to perform while reaching.
2. Performing the movement disturbed the posture.
Example: When a movement in the hip must be performed during standing, it is necessary to lift the feet from the ground (or bend the knees), which disturbs the standing position. The same holds for all movements in the knee.

| **Posture** | **Joint** | **Movement that cannot be performed freely** |
|---|---|---|
| Sitting | Hip | Flexion<br>Extension<br>Adduction<br>Abduction<br>Endorotation<br>Exorotation |
| Standing | Hip | Flexion<br>Extension<br>Adduction<br>Abduction<br>Endorotation<br>Exorotation |
| | Knee | Flexion<br>Extension<br>Abduction<br>Adduction<br>Rotation inwards<br>Rotation outward |
| Walking | Hip | Flexion<br>Extension<br>Adduction<br>Abduction<br>Endorotation<br>Exorotation |
| | Knee | Flexion<br>Extension<br>Abduction<br>Adduction<br>Rotation inwards<br>Rotation outward |
| | Ankle | Flexion<br>Extension<br>Inversion<br>Eversion |
| | Toe joints | Extension |
| Stooping | Spine | Extension |
| Reaching | Scapula and clavicle | Depression<br>Retraction |
| | Shoulder | Retroversion |

# D Overview of analysis movements by using three selection criteria

The table below shows how all movements are judged by the three selection criteria. A red box means that the movement does not fulfil the criterion, a green box means that the criterion is fulfilled. To get only the most optimal movements, only the movements judged with three green boxes are considered suitable for control. These movements are: flexion in the toe joints, elevation of the scapula, protraction in the sternoclavicular joint, lateral flexion of the spine and lateral rotation of the spine.

| Movement | Daily movement? | Posture independent? | Influence on position terminal device? |
|---|---|---|---|
| **Hip** | | | |
| Flexion | red | red | green |
| Extension | red | red | green |
| Adduction | green | red | green |
| Abduction | green | red | green |
| Endorotation | green | red | green |
| Exorotation | green | red | green |
| **Knee** | | | |
| Flexion | red | red | green |
| Extension | red | red | green |
| Rotation inwards | green | red | green |
| Rotation outwards | green | red | green |
| **Toe joints** | | | |
| Flexion | green | green | green |
| Extension | red | red | green |
| **Ankle** | | | |
| Flexion | red | red | green |
| Extension | red | red | green |
| Inversion | green | red | green |
| Eversion | green | red | green |
| **Shoulder** | | | |
| Exorotation | green | green | red |
| Endorotation | green | green | red |
| Adduction | red | green | red |
| Abduction | red | green | red |
| Anteversion | red | green | red |
| Retroversion | red | green | red |
| **Elbow and radioulnar joint** | | | |
| Flexion | red | green | red |
| Extension | red | green | red |
| Supination | red | green | red |
| Pronation | red | green | red |
| **Scapula and clavicle** | | | |
| Depression | green | red | green |
| Elevation | green | green | green |
| Protraction | green | green | green |
| Retraction | green | red | green |
| **Spine** | | | |
| Ventral flexion | red | green | green |
| Dorsal extension | red | red | green |
| Lateral flexion | green | green | green |
| Lateral rotation | green | green | green |

# E Demographic data

The table below shows the body dimensions measured over all subjects. To measure these dimensions, the measuring methods of Dined are used. To investigate whether the group of subjects is a good sample of the population, the values were compared to data from Dined (20-30 years, males and females, 2004). A significance level of 0.05 is used to identify significant differences.

The participants of this study have a lower weight, smaller width of the shoulders and a larger sitting height. For all other dimensions, the participants of this study are a good sample of the population.

**Table 3: Body dimensions of subjects, compared to demographic data from Dined.**

| | Mean ± SD | Range | Demographic data (Mean ± SD) | Significant difference? |
|---|---|---|---|---|
| **Age (years)** | 25.3 ± 1.5 | 21-28 | | |
| **Weight (kg)** | 68.8 ± 8.8 | 55-84 | 73 ± 13 | Significant (p=.038) |
| **Height (cm)** | 176.9 ± 8.9 | 157-196 | 176.1 ± 10.9 | Not significant (p=.675) |
| **Width of shoulders (cm)** | 38.5 ± 3.6 | 32-46 | 44.4 ± 34 | Significant (p=.000) |
| **Sitting height (cm)** | 94.4 ± 3.2 | 89-100 | 92.0 ± 51 | Significant (p=.004) |
| **Waist circumference (cm)** | 79.4 ± 7.4 | 68-91 | 82.4 ± 13.3 | Not significant (p=.080) |

# F Informed consent

Delft Institute of Prosthetics and Orthotics

Innovative Upper Extremity Prostheses and Orthoses

**Krachten en verplaatsingen 'dubbel-gestuurde-armprothese'**

Bewegingsgestuurde armprotheses gebruiken de kracht en beweging van gezonde lichaamsdelen om de prothese aan te sturen. Door bijvoorbeeld de aangedane arm naar voren te bewegen opent de kunsthand, wanneer de arm weer terug naar het lichaam wordt bewogen, sluit de hand vanzelf. De protheses die nu gebruikt worden kunnen vrijwillig geopend of gesloten worden, één van de acties (openen dan wel sluiten) vindt altijd automatisch (onvrijwillig) plaats.

Voor de patiënt zou het wenselijk zijn als beide bewegingen vrijwillig kunnen worden aangestuurd. Hierdoor heeft de patiënt de volledige controle over de bewegingen van zijn of haar prothese. Hoe zo'n 'dubbel-gestuurde-prothese' aangestuurd kan worden door de patiënt is nog niet onderzocht. In dit experiment zal worden gekeken naar de bewegingsuitslag en krachten die behaald kunnen worden met enkele bewegingen, die eventueel gebruikt zouden kunnen worden voor de aansturing van een armprothese.

Het experiment zal worden uitgevoerd door Ellen van Mil. Tijdens het experiment zal je 10 verschillende bewegingen uitvoeren (zie tabel 1 op pagina 2). Je neemt plaats op een stoel met daarop een houten plank. Afhankelijk van de gemeten beweging wordt er een strakke band om je borst gebonden of om je teen en voet. Dit kan voor enigszins ongemak zorgen, maar zal absoluut geen pijn doen. De krachtsensor zal de kracht meten die je produceert door een beweging uit te voeren. Elke beweging wordt ongeveer 15 keer uitgevoerd.

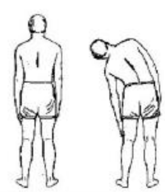
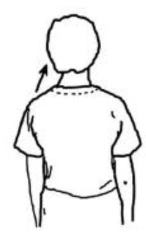
Tijdens het experiment zal een video worden opgenomen waarop de bewegingen die je uitvoert te zien zullen zijn. Deze video is geanonimiseerd, net als de gemeten data. Alleen de onderzoeker heeft toegang tot de sleutel om de video en gemeten data met de bijbehorende persoon te verbinden. Tussen het meten van de krachten door, zal je enkele vragenlijsten invullen over de bewegingen die je uitgevoerd hebt. In totaal zal het experiment ongeveer twee uur in beslag nemen.

Deelname aan het onderzoek is vrijwillig. Het experiment is goedgekeurd door de ethische toetsingscommissie van de TU Delft. Alle informatie zal strikt vertrouwelijk behandeld worden. Er zal zorg voor gedragen worden dat het gebruiken van de resultaten van het onderzoek zonder mogelijke identificatie van de participanten gebeurt. Je mag op ieder moment het onderzoek stopzetten en de toestemming alsnog intrekken.

*Ik heb dit formulier gelezen en vind het goed om deel te nemen aan het onderzoek,*

| | |
|---|---|
| ……………………………………………………………. | ………………………………………………………. |
| Datum | Handtekening participant |

| **Hoofdonderzoeker** | **Supervisor 1** | **Supervisor 2** |
|---|---|---|
| TU Delft | TU Delft | TU Delft |
| E. van Mil | Dr. Ir. D.H. Plettenburg | M. Hichert |
| T: 06-53782243 | T: 015-2785615 | T: 015-2785241 |
| E: E.H.A.vanMil@student.tudelft.nl | E: d.h.plettenburg@tudelft.nl | E: m.hichert@tudelft.nl |

| | |
|---|---|
| Lateral rotation trunk |  |
| Lateral flexion trunk |  |
| Elevation shoulder |  |
| Protraction shoulder |  |
| Flexion toes |  |

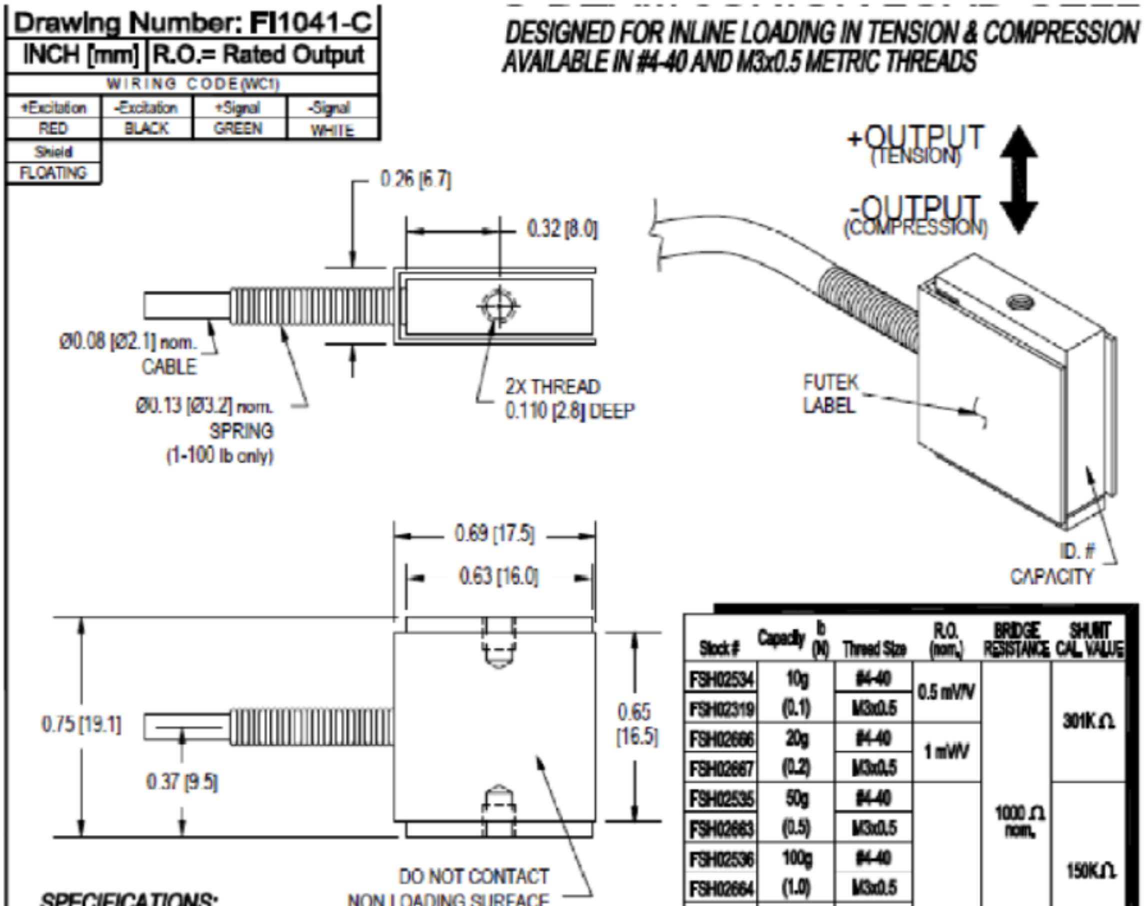
**Tabel 1: Uit te voeren bewegingen tijdens experiment. Alle bewegingen zullen zowel links als rechts worden uitgevoerd.**

2

# G Specifications measurement setup

## G.1 Load cell

# MODEL FLLSB200 S-BEAM Junior Loadcell




***SPECIFICATIONS:***

| | |
|---|---|
| RATED OUTPUT | SEE CHART |
| SAFE OVERLOAD | 1000% of R.O.<br>200% of R.O. Tension Only (50-100 lb)* |
| ZERO BALANCE** | ±3% of R.O., ±5% of R.O. (10-20g) |
| EXCITATION (VDC OR VAC) | 10 Max |
| BRIDGE RESISTANCE | SEE CHART |
| NONLINEARITY | ±0.1% of R.O. |
| HYSTERESIS | ±0.1% of R.O. |
| NONREPEATABILITY | ±0.05% of R.O. |
| TEMP. SHIFT ZERO | ±0.01% of R.O./°F [0.018% of R.O./°C] |
| TEMP. SHIFT SPAN | ±0.02% of LOAD/°F [0.036% of LOAD/°C] |
| COMPENSATED TEMP. | 60 to 160°F [15 to 72°C] |
| OPERATING TEMP. | -60 to 200°F [-50 to 93°C] |
| MATERIAL | ALUMINUM (10g-10lb), STAINLESS STEEL (25-100lb) |
| WEIGHT | 0.3 oz [9 g] |
| DEFLECTION | 0.003-0.005 [0.07-0.13] |

CABLE: #29 AWG, 4 Conductor, Spiral Shielded Silicone Cable, 5 ft [1.5 m] Long

ACCESSORIES AND RELATED INSTRUMENTS AVAILABLE

| | |
|---|---|
| CALIBRATION (STD) | 5 pt TENSION; SEE CHART FOR SHUNT CAL VALUE. |
| CALIBRATION (AVAILABLE) | COMPRESSION |
| CALIBRATION TEST EXCITATION | 5 VDC |

*SENSOR STRUCTURE CAN HANDLE HIGH OVERLOADS BUT #4-40 and M3x0.5 THREADS MAY LIMIT OVERLOAD AT HIGHER CAPACITY

** ZERO BALANCE IS BASED ON LAYING SENSOR ON ITS SIDE (THREADS HORIZONTAL)

| Stock # | Capacity lb (N) | Thread Size | R.O. (nom.) | BRIDGE RESISTANCE | SHUNT CAL VALUE |
|---|---|---|---|---|---|
| FSH02534 | 10g | #4-40 | 0.5 mV/V | 1000 Ω nom. | 301K Ω |
| FSH02319 | (0.1) | M3x0.5 | | | |
| FSH02666 | 20g | #4-40 | 1 mV/V | | |
| FSH02667 | (0.2) | M3x0.5 | | | |
| FSH02535 | 50g | #4-40 | 2 mV/V | | 150K Ω |
| FSH02663 | (0.5) | M3x0.5 | | | |
| FSH02536 | 100g | #4-40 | | | |
| FSH02664 | (1.0) | M3x0.5 | | | |
| FSH02602 | 250g | #4-40 | | | |
| FSH02665 | (2.5) | M3x0.5 | | | |
| FSH00091 | 1 | #4-40 | | 350 Ω nom. | 60.4K Ω |
| FSH00101 | (4.5) | M3x0.5 | | | |
| FSH00092 | 2 | #4-40 | | | |
| FSH00102 | (8.9) | M3x0.5 | | | |
| FSH00093 | 5 | #4-40 | | | |
| FSH00103 | (22.2) | M3x0.5 | | | |
| FSH00095 | 10 | #4-40 | | | |
| FSH00104 | (44.5) | M3x0.5 | | | |
| FSH00096 | 25 | #4-40 | | | |
| FSH00105 | (111) | M3x0.5 | | | |
| FSH00097 | 50 | #4-40 | | | |
| FSH00106 | (222) | M3x0.5 | | | |
| FSH00098 | 100 | #4-40 | | | |
| FSH00107 | (445) | M3x0.5 | | | |


**Feteris Components B.V.**
Scheveningseweg 15
2517 KS The Hague
The Netherlands
+31 70 3924421
+31 70 3644249
www.feteriscomponents.com
sales@feteriscomponents.nl
Offices in: Benelux | France | Germany | United Kingdom | USA | Italy
FETERIS components
Sensors & M.M.I. Products

## G.2 Amplifier

**Conditionneur de signal analogique**
*Analog signal conditioner*

# CPJ / CPJ2S

## ±10 V/0-10 V / 4-20 mA

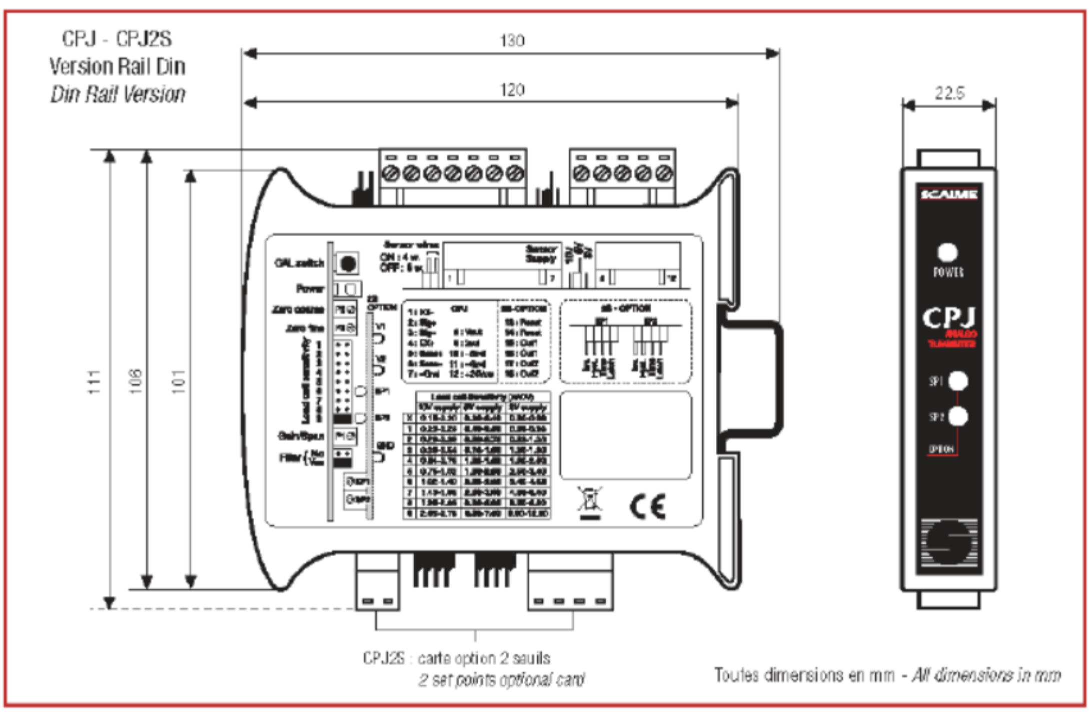
- Conditionne jusqu'à 4 capteurs à jauges de contrainte (350 Ω)
- Capteur 4 ou 6 fils
- Sortie tension (±10 Vdc ou 0-10 Vdc) et sortie courant (4-20 mA)
- Signal d'étalonnage par shunt
- 2 seuils sur relais en option (CPJ2S)

- *The CPJ is able to run up to 4 strain gauge load cells (350 Ω)*
- *4 or 6 wire load cell*
- *Voltage output (±10 Vdc or 0-10 Vdc) and current ouput (4-20 mA)*
- *Shunt calibration signal*
- *2 set points on relays optional version CPJ2S*


Version Rail DIN
*DIN Rail Version*

Version Carte
*Board Version*

Version Boîtier
*Housing Version*



# CPJ/CPJ2S

**Conditionneur de signal analogique**
*Analog signal conditioner*

## Caractéristiques CPJ - *CPJ Specifications*

| | | | |
|---|---|---|---|
| Alimentation | *Power supply* | 24 ±4 | Vdc |
| Classe de précision | *Accuracy class* | 0.05 | % |
| Effet température sur le zéro | *Temperature effect on zero* | ≤0.035 | %F.S.*/°C |
| Effet température sur le gain | *Temperature effect on span* | ≤0.02 | %/°C |
| Plage de température de fonctionnement | *Operating temperature range* | 0...+70 | °C |
| Alimentation capteur (commutable par cavalier) | *Load cell input voltage (engaged with jumper)* | 3, 5, 10 | Vdc |
| Impédance min. capteur : alim. capteur 3/5 V<br>alim. 10 V | *Min. load cell impedance: excit. 3/5 V*<br>*excit. 10 V* | 80<br>160 | Ω<br>Ω |
| Réglage du gain | *Span adjustment* | 0.15...12 | mV/V |
| Consommation max. CPJ / CPJ2S | *Max supply current CPJ / CPJ2S* | 120 / 170 | mA |
| Sortie tension | *Voltage output* | ±10, 0-10 | V |
| Sortie courant | *Current output* | 4-20 | mA |
| Impédance de charge en sortie tension | *Load impedance for voltage output* | ≥ 2000 | Ω |
| Impédance de charge en sortie courant | *Load impedance for current output* | ≤ 500 | Ω |
| Charge capacitive en sortie | *Capacitive load on the output* | ≤ 1 | nF |
| Filtre (commutable par cavalier) passe bas (-3 dB) | *Filtering (engaged with jumper) low pass (-3dB)* | 10 | Hz |
| Bande passante | *Bandwidth* | ≤ 20 | KHz |

## Caractéristiques points de consignes CPJ2S - *CPJ2S Set points specifications*

| | | | |
|---|---|---|---|
| GÉNÉRALES | *GENERAL* | | |
| Nombre de points de consigne | *Number of set points* | 2 | |
| Réglage | *Adjustment* | 2 potentiomètres<br>*2 potentiometers* | |
| Sens de fonctionnement réglable | *Selectable functionning direction* | Oui - *yes* | |
| Hystérésis | *Hysteresis* | 1.1 / 0.2 | % F.S.* |
| Temps de maintien | *Holding time* | 5 / 600 | ms |
| Fonction vérouillage relais | *Latch function* | Oui - *yes* | |
| Temps de réponse | *Response time* | 7 | ms |
| RELAIS | *RELAY* | | |
| Type | *Technology* | Statiques opto-isolés<br>*Photorelays* | |
| Courant max. à 40°C | *On-state current max. at 40°C* | 0.4 | A |
| Tension max. à l'état ouvert | *Off-state voltage* | 55 | V |
| Résistance à l'état passant | *On-state resistance* | 2 | Ω |
| Tension d'isolement | *Isolation voltage* | 2 500 | Vrms |

* F.S. : Pleine échelle - *Full scale*

## Options - *Options*

| | | | |
|---|---|---|---|
| Entrée potentiomètre | *Input for potentiometer* | | |
| Filtre personnalisé | *Customized filtering* | 0.5...450 | Hz |
| Alimentation 12 Vdc** | *Power supply 12 Vdc*** | | |

** Sortie tension limitée à ±5, 0-5 V - *Output voltage limited to ±5, 0-5 V*

SCAIME
L'INFINIMENT PRECIS INFINITE PRECISION
BP501 - F 74105 Annemasse Cedex
Tél. : (+33) 4 50 87 78 64
Fax : (+33) 4 50 87 78 42
E.mail : info@scaime.com

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Agent

FT-CPJ-CPJ2S-FE-1106 - SCAIME - SIREN 389 325 283 - R.C.S. THONON LES BAINS - SIRET 389 325 283 00015 - SCAIME se réserve le droit d'apporter toutes modifications sans avis préalable - SCAIME reserves the right to bring any modification without prior notice.

## G.3 Data acquisition system

### Low-Cost Multifunction DAQ for USB

## Specifications

Typical at 25 °C unless otherwise noted.

### Analog Input

**Absolute accuracy, single-ended**

| Range | Typical at 25 °C (mV) | Maximum (0 to 55 °C) (mV) |
|---|---|---|
| ±10 | 14.7 | 138 |

**Absolute accuracy at full scale, differential[1]**

| Range | Typical at 25 °C (mV) | Maximum (0 to 55 °C) (mV) |
|---|---|---|
| ±20 | 14.7 | 138 |
| ±10 | 7.73 | 84.8 |
| ±5 | 4.28 | 58.4 |
| ±4 | 3.59 | 53.1 |
| ±2.5 | 2.56 | 45.1 |
| ±2 | 2.21 | 42.5 |
| ±1.25 | 1.70 | 38.9 |
| ±1 | 1.53 | 37.5 |

Number of channels ........ 8 single-ended/4 differential
Type of ADC ........ Successive approximation

**ADC resolution (bits)**

| Module | Differential | Single-Ended |
|---|---|---|
| USB-6008 | 12 | 11 |
| USB-6009 | 14 | 13 |

**Maximum sampling rate (system dependent)**

| Module | Maximum Sampling Rate (kS/s) |
|---|---|
| USB-6008 | 10 |
| USB-6009 | 48 |

Input range, single-ended ........ ±10 V
Input range, differential ........ ±20, ±10, ±5, ±4, ±2.5, ±2, ±1.25, ±1 V
Maximum working voltage ........ ±10 V
Overvoltage protection ........ ±35 V
FIFO buffer size ........ 512 B
Timing resolution ........ 41.67 ns (24 MHz timebase)
Timing accuracy ........ 100 ppm of actual sample rate
Input impedance ........ 144 k
Trigger source ........ Software or external digital trigger
System noise ........ 0.3 $LSB_{rms}$ (±10 V range)

### Analog Output

Absolute accuracy (no load) ........ 7 mV typical, 36.4 mV maximum at full scale
Number of channels ........ 2
Type of DAC ........ Successive approximation
DAC resolution ........ 12 bits
Maximum update rate ........ 150 Hz, software-timed
Output range ........ 0 to +5 V
Output impedance ........ 50 Ω
Output current drive ........ 5 mA
Power-on state ........ 0 V
Slew rate ........ 1 V/µs
Short-circuit current ........ 50 mA

### Digital I/O

Number of channels ........ 12 total
8 (P0.<0..7>)
4 (P1.<0..3>)
Direction control ........ Each channel individually programmable as input or output
Output driver type
USB-6008 ........ Open-drain
USB-6009 ........ Each channel individually programmable as push-pull or open-drain
Compatibility ........ CMOS, TTL, LVTTL
Internal pull-up resistor ........ 4.7 kΩ to +5 V
Power-on state ........ Input (high impedance)
Absolute maximum voltage range ........ -0.5 to +5.8 V

**Digital logic levels**

| Level | Min | Max | Units |
|---|---|---|---|
| Input low voltage | -0.3 | 0.8 | V |
| Input high voltage | 2.0 | 5.8 | V |
| Input leakage current | – | 50 | µA |
| Output low voltage (I = 8.5 mA) | – | 0.8 | V |
| Output high voltage (push-pull, I = -8.5 mA) | 2.0 | 3.5 | V |
| Output high voltage (open-drain, I = -0.6 mA, nominal) | 2.0 | 5.0 | V |
| Output high voltage (open-drain, I = -8.5 mA, with external pull-up resistor) | 2.0 | – | V |

### Counter

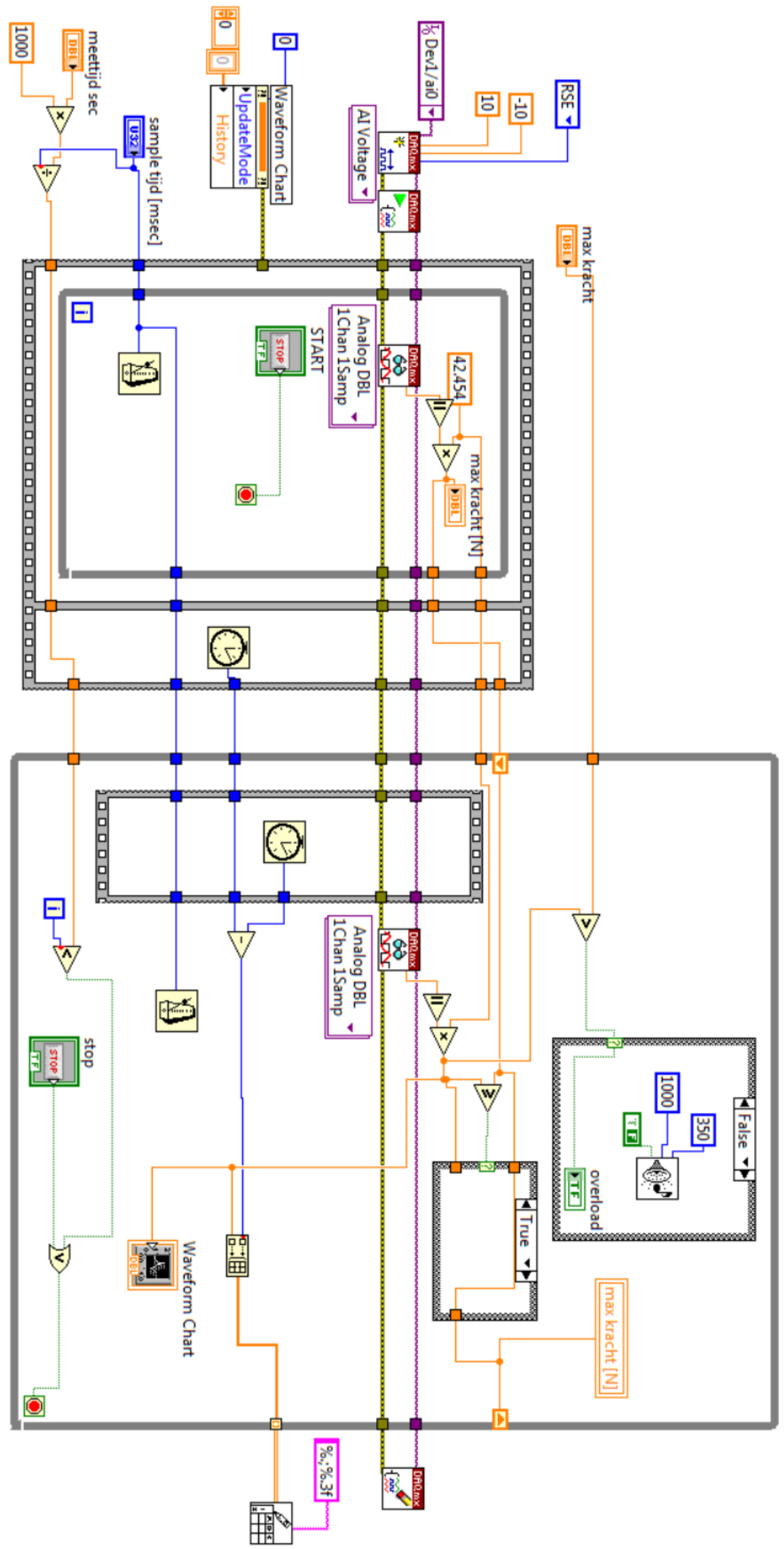
Number of counters ........ 1
Resolution ........ 32 bits
Counter measurements ........ Edge counting (falling edge)
Pull-up resistor ........ 4.7 kΩ to 5 V
Maximum input frequency ........ 5 MHz
Minimum high pulse width ........ 100 ns
Minimum low pulse width ........ 100 ns
Input high voltage ........ 2.0 V
Input low voltage ........ 0.8 V

**Power available at I/O connector**

+5 V output (200 mA maximum) ........ +5 V typical, +4.85 V minimum
+2.5 V output (1 mA maximum) ........ +2.5 V typical
+2.5 V output accuracy ........ 0.25% max
Voltage reference temperature drift ........ 50 ppm/°C max

[1] Input voltages may not exceed the working voltage range.

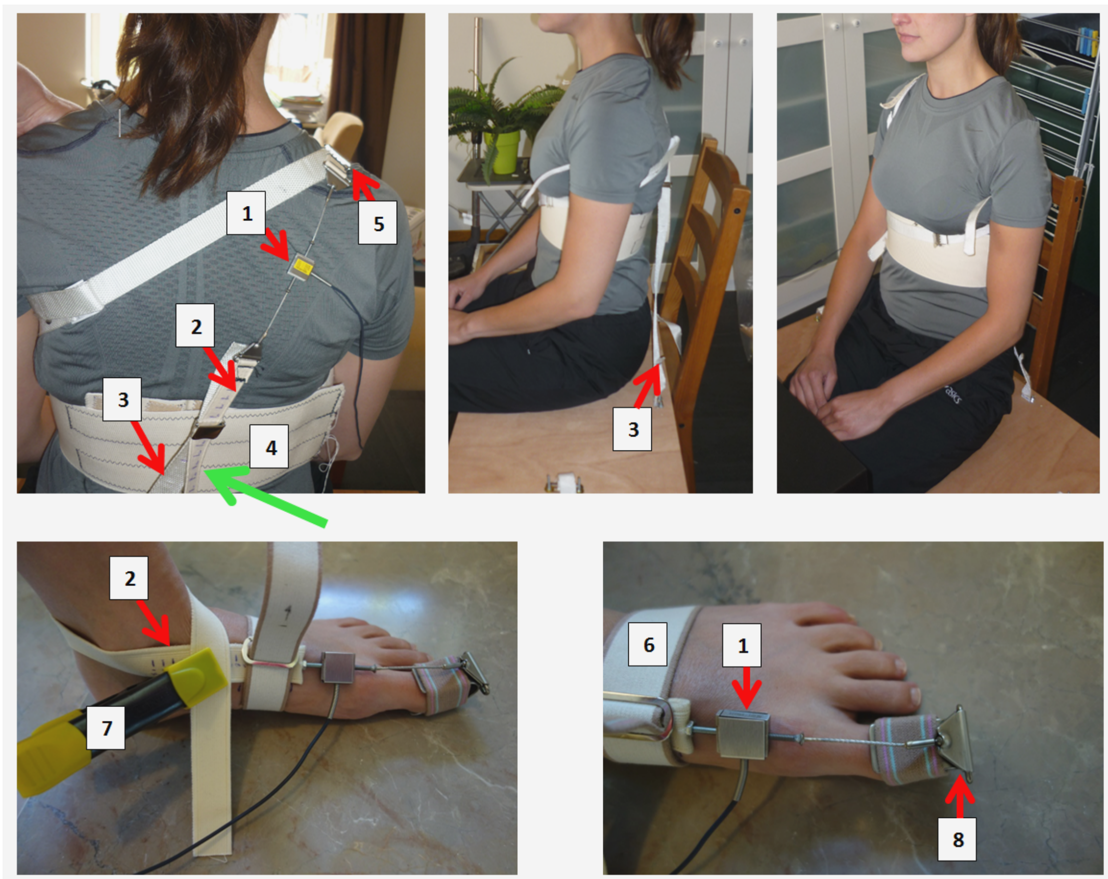
## G.4 LabVIEW-Block diagram



# H Pictures measurement equipment

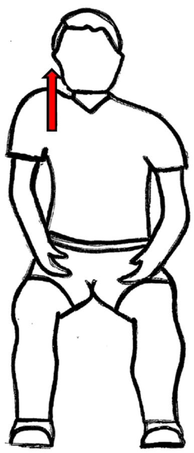
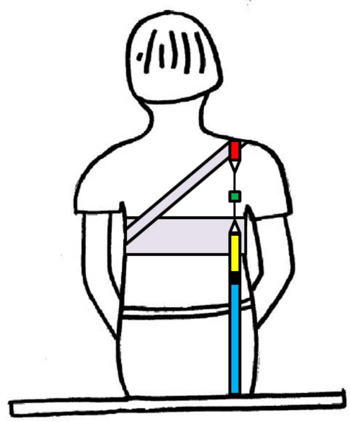
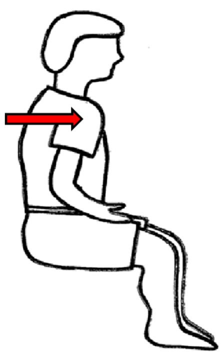
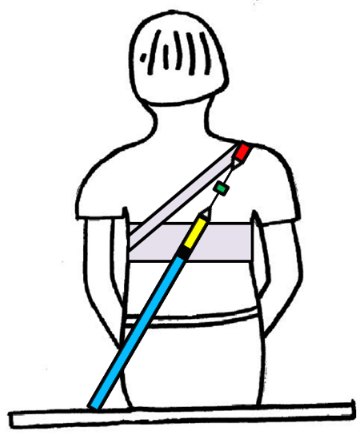
The pictures below show the measurement setup while measuring protraction forces of the right shoulder. The different objects are:
1. Force sensor
2. Measurement strap with markings
3. Strap attached to wooden board
4. Chest strap
5. Attachment strap
6. Foot strap
7. Plier to fix length of measurement strap foot
8. Iron socket

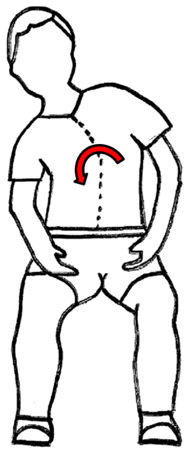
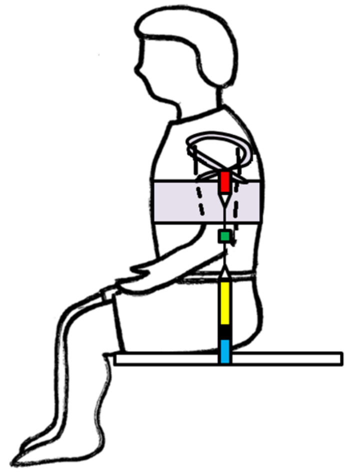
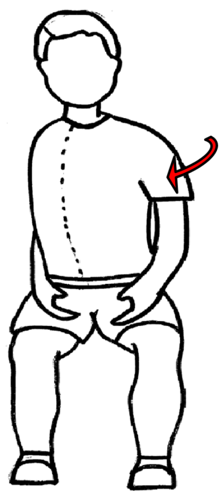
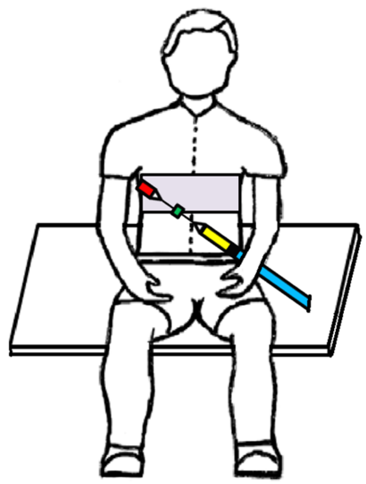
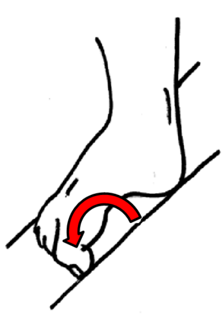
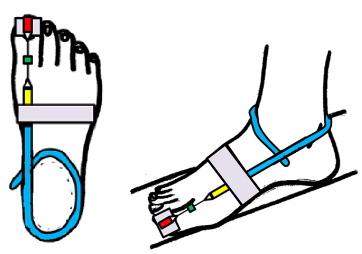
The green arrow indicates the location where the locking plier is placed to fix the length of the measurement strap.



# I Instructions and setup equipment per movement

**Equipment setup and instructions given to measure operating forces and displacements for each movement. The table shows only the situations where the force is measured at the right side of the body. For the left side, the setup was similar but mirrored. Grey: chest strap/foot strap and iron socket, red: strap attached to chest strap/strap attached to iron socket, blue: strap attached to wooden board/strap around ankle, yellow: measurement strap, green: load cell, black: clasp/plier for foot.**

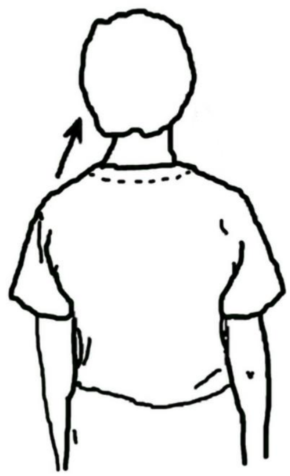
| Movement | Equipment setup | Instruction |
|---|---|---|
| Elevation shoulder  |  | Elevate the shoulder, without rotating the trunk or bringing the ear towards the shoulder. Keep both hands on the upper legs without exerting force. |
| Protraction shoulder  |  | Push the shoulder forwards, without rotating the upper part of the trunk. Keep both hands on the upper legs without exerting force. |

| **Movement** | **Equipment setup** | **Instruction** |
|---|---|---|
| Lateral flexion trunk  |  | Flex the trunk by bringing the shoulder towards the hip, like you need to roll the side of the trunk over a bar which is placed in between the hip bone and the lowest point of the ribcage. Do not translate the complete upper body sideward, but only make a bending movement. By doing this, the contralateral side is stretched. Do not lift the buttocks from the wooden board. |
| Rotation trunk  |  | Make a torsional rotation with the trunk, which makes the shoulder move backwards. Do not rotate the neck, but keep looking forward. Do not lift the buttocks from the wooden board. |
| Flexion toes  |  | Flex the toes. By doing this, the middle foot will unstick the ground, however the top of the toes keeps in contact with the ground. |

# J Questionnaire subjective perception - Example for elevation shoulder left

**Nummer pp:**

***<u>Elevation shoulder (left)</u>***



**Question 1: Please fill in the following statements:**

| | **Strongly agree** | **Tend to agree** | **Neither agree nor disagree** | **Tend to disagree** | **Strongly disagree** |
|---|---|---|---|---|---|
| *The movement was easy to perform* | ☐ | ☐ | ☐ | ☐ | ☐ |
| *I had to think how to perform the movement* | ☐ | ☐ | ☐ | ☐ | ☐ |
| *Performing the movement felt uncomfortable* | ☐ | ☐ | ☐ | ☐ | ☐ |

**Question 2: Did it hurt to perform the movement?**

Yes ○ (Go to question 3)

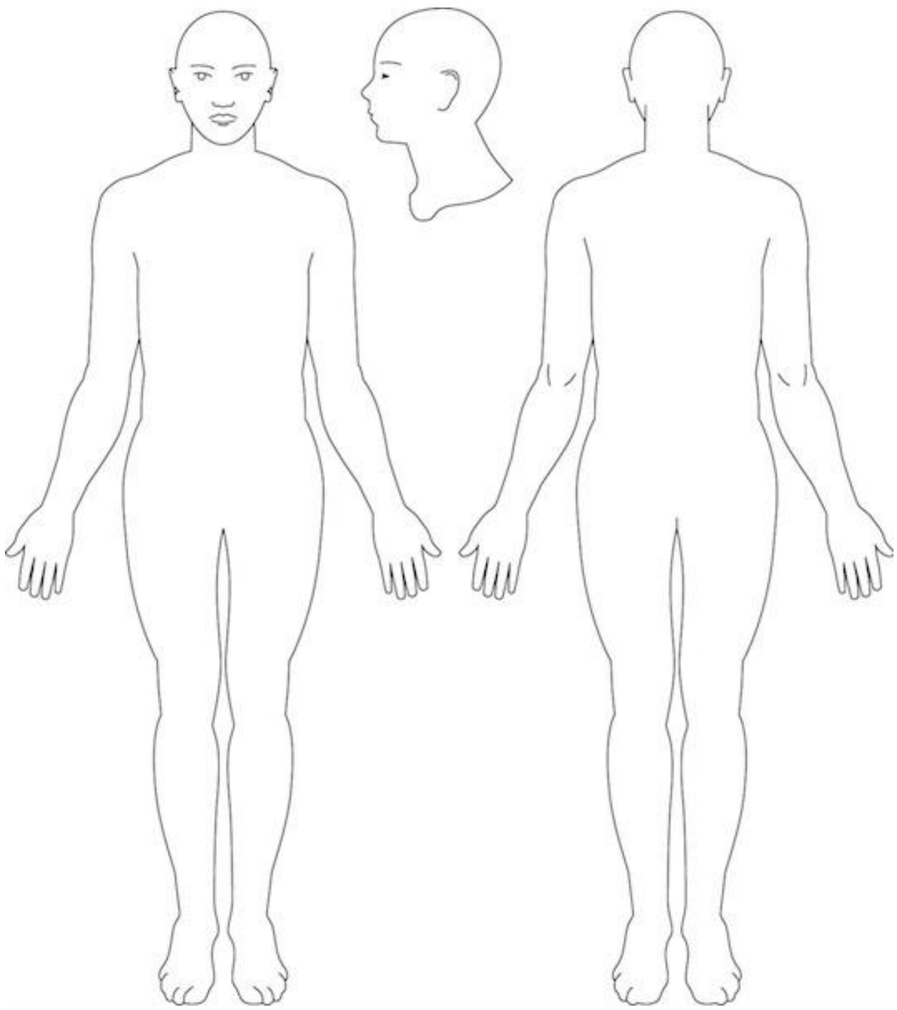
No ○ (The questionnaire is finished)

**Question 3: Can you indicate in the body map where you felt the pain?**

Color the region where you felt the pain. Use the orange pencil to indicate little pain, use the red pencil to indicate heavy pain.

| Nummer pp: |
|---|

# Bodymap



| | |
|---|---|
| | Little pain |
| | Heavy pain |