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Data acquisition of kinesiological experiments

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Data acquisition of kinesiological experiments

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Chapter 1

Introduction

Kinesiological experiments are developed to analyse the dynamic behaviour of human beings. In this report the research on two experiments is described. The kinesiological experiments are developed by the Department of Movement Sciences of the University of Limburg. Both experimental setups are realised in cooperation with the Eindhoven University of Technology. Although both experiments are not part of the same kinesiological research field, they are considered together in this computational and experimental mechanical research. This research focuses on the data acquisition and the dynamic behaviour of the experiments. The technological approach is identical for both experiments. Identical hardware and software are used to make the desired information available.

The movement science analysis of the human dynamic behaviour is comparable with the dynamics and control analysis of mechanics. A machine performing controlled actions in interaction with its environment, consists usually of three units. Sensory units provide information on the actual state of the subject and its environment. Based on this information, control units generate response signals to adjust the actions of the subject. The response actions are carried out by motor units.

In contrast to mechanical systems it is more difficult to comprehend the control system of the human being. There are two approaches to study system behaviour.

- The first approach considers a system in a state description. A system can be simulated by modelling the dynamic behaviour. The properties of every detail and the interactions between the different parts are known or estimated. This way, the transfer function between input and response can be predicted.

- The second, the black-box approach is used when the specific system parameters are not available. The transfer relation between input and response of the system is determined by generating an input signal for the system and measuring the response.

Living creatures consist of many microscopic parts, subsystems that are all connected in a complex way. Even when it is possible to describe the behaviour of a small subsystem, it is difficult to connect it to the whole system. Separating subsystems for research, causes further problems as the properties of these nonliving parts are changed. Kinesiologists often use the black-box approach to investigate dynamic behaviour.

The goal directed movement with collision experiment (movement experiment) is used to analyse human control properties of goal directed arm and hand movements. The system of the human being that performs and controls the hand movements, is considered as one total system, a
black-box. This experiment is developed to determine an aspect of the human control behaviour, the relation between the accuracy and the speed of a certain motion. One can imagine that a task more complex to perform results in a slower execution of this motion. It is more difficult to control the more accurate motion. Its performance requires more specific sensory information.

The technological objective of the movement experiment research is to measure and process kinesiological interesting information. Different receptors are used to provide information signals to describe the performed experimental runs. Parameters, that characterise the experiment, are derived from these data signals. These parameters distinct differences between responses on different experimental conditions. The validity of these parameters is investigated. Appropriate parameters can be used in this and future movement science experiments.

The second kinesiological experiment investigates properties of a specific part of the total kinetic system of a living organism, the motor unit. The kinesiological objective of the dynamometer experiment is to investigate adaption and damage of muscle fibres. The dynamometer is the apparatus, that is used to (over)load these muscles. It fatigue the muscle and measures the effects on the muscle properties. In this research the muscle behaviour is regarded independently of the rest of the control system. The muscle fibres are fatigued by external stimulation. A voltage potential current connected to the muscle fibre attachments generates muscle activity. The dynamometer measures the prescribed motion and the generated torque during the fatiguing test.

The technological objective of the dynamometer experiment research is to make the required signals available for processing and analysis. One is interested in the operating range of the dynamometer. Therefore the experimental setup has to be made suitable for gauging experiments. A description of the dynamic behaviour of the apparatus is desirable for simulation and gauging purposes.

Both experiments are described independently of each other in separate chapters. Chapter 2 describes the research on the goal directed movement with collision experiment. The work on the rat dynamometer is described in Chapter 3. Finally the general conclusions of realising and analysing kinesiological experiments are stated in Chapter 4.
Chapter 2

Goal directed movements with collision

2.1 Introduction

The goal directed movement with collision experiment (movement experiment) is part of the research interested in specific human movement control properties. The experiment is set up to investigate the correlation between the movement accuracy and speed of goal directed movements. In this research field the movement control system is considered as a black-box. The total response caused by a specific input is measured. This means no distinction is made between the separate units providing the three distinguishable control tasks: sensory, control, and motor units.

The control strategies performing movements are studied by measuring the response to various experimental conditions. Experimental measurement setups are developed to analyse the influence of multi-segmented movements, limitations on the preparation period, or reversal movements. Chamberlin & Magill [4] and Fischman & Gilmour Reeve [5] have investigated the one-target advantage between single and multi-segmented movements. They researched to what extent, On-line or feed-forward programming control movements.

Most experiments in this area use goal directed movements of the hand. The hand holds a stylus and performs a predetermined movement. In general movement and reaction times are used as parameters to indicate significant differences between movement responses caused by various experimental conditions. Adam et al. [6] and Adam et al. [7] use the generated electromyography (EMG) activity and the storage of elastic energy to indicate experimental responses.

Teasdale & Schmidt [1] have introduced the impact force as indication parameter. The aim of their experiment was to examine modifications in the control strategy as a function of the amount of impact force a subject is allowed to use to decelerate the movement of his hand. The goal directed movement with collision experiment is developed to verify the use of the impact force as parameter to characterise the response on various experimental conditions.

Experimental conditions such as, the magnitude of the goal, the complexity of the movement, and the accuracy with which the movement has to be performed, influence the velocity of the execution of the experiment. A goal directed movement consists of acceleration and deceleration phases before reaching the goal. The acceleration and deceleration patterns are the consequence of control actions during movement. The movement is stronger decelerated when it is more difficult to reach the goal. This results in a lower movement speed just before landing, causing a smaller impact when landing.
The experimental measurement setup of the movement experiment ensures the subject to complete a predetermined trajectory. The subject has to hold a stylus, a pen and move it from a start to a target point. During the experiment one or two sequential predetermined movement steps have to be performed. The total movement is executed between one start and two target points. All experiments start on the start point \( P_0 \) and move to the first target point \( P_1 \). Depending on the given instructions, subjects have to stop here (1) or move on to the second target point \( P_2 \) and stop there (2), see Figure 2.1. Another way to change the experimental conditions is to use other target diameters.

**Figure 2.1: The movement experiment.** Subjects are instructed to move the pen with a one-step (1) or a two-step (2) movement from the start point \( P_0 \) to the target point(s) \( P_1 \) (and \( P_2 \)).

Movement times and landing impact quantities characterise the movement properties. The movement times indicate how fast the motion phases of the movement are performed. A more complex movement is performed slower, it takes a longer period of time. The impact quantities are an indication for the extent of the deceleration of the movement just before landing. A less controlled movement generates a larger collision impact. Besides the use of the landing force, also the use of the landing impulse and the landing velocity are considered as characterising parameters.

The objective of this research is to measure the movement times and the landing impact quantities accurately. This parameters have to characterise differences in responses on changing experimental conditions. Therefore appropriate measurement transducers have to be used. These transducers have to be built in a data acquisition and data processing environment. The sample rate, necessary to fulfil the accuracy requirements for the characterising parameters, has to be determined. Finally the software to process the data has to be written.

In Section 2.2 the measurement methods and materials are described. Next the performed measurements are analysed in Section 2.3. The suitability of the resulting characterising parameters is discussed in Section 2.4. Section 2.5 states the conclusions and recommendations of the goal directed movement with collision experiment.
2.2 Measurement methods

2.2.1 Experimental measurement setup

The experiment is performed by moving a stylus, a pen from a start to one or two target points. The total measurement setup consists of: the experiment setup, measuring transducers, hardware to collect the measured data, and software to process the data.

The target points are placed in a plateau. They are positioned in a straight line. The centre points lie on 10 cm distance from each other. The targets used to obtain various experimental conditions, have either a 6, 12, or 24 mm diameter.

In course of the research two styli are used. The first pen is a solid metal pen with a brass pen tip. The other pen is modified with a synthetic layer. This 3mm thick layer is positioned between pen tip and pen shaft. When the pen collides with the target, this layer damps the dominating mass of the pen shaft during collision. The modified pen has approximately twice the mass of the original pen, 103 against 52 gram. The modified pen is equipped to use acceleration transducers on the top of the pen. Both pens are suited to use in an electronical conducting circuit.

2.2.2 Measurements

Characteristic parameters represent movement properties of the subject. The properties are measured with transducers during the whole experimental period. The measured signals are processed on to the desired parameters. The parameters are: the movement and dwell times, the landing force, the landing impulse, and the landing velocity.

Movement and dwell times

The movement and dwell times are the time length of the periods that a corresponding state continues. The state of the experiment is measured during the whole experiment. To measure the time period a state continues, the time points where the state of the experiment changes are determined. The length of a period is the subtraction of its two state transition time points.

The time reference voltage signal $V_{tr}$ shows continuously the state of the experiment. Four voltage levels distinguish four corresponding experimental states. The four experimental states are: pen contacts start point $P_0$; pen contacts target point one $P_1$; pen contacts target point two $P_2$; and pen is free in the air $P_r$. No distinction is made between the state that the pen is free in the air between start point and target point one and the state that the pen is free in the air between target point one and target point two. A step in the voltage level of the signal detects the transition between two movement states. These transition points are the desired time points.

Movement time one, $MT_1$ is the movement period between start point and target point one. The dwell time, $DT$ is the period the pen makes contact with target point one. Movement time two, $MT_2$ is the movement period between target point one and target point two. These periods are separated by: the start time point $T_0$ from the start point; the landing time point $T_1$ on target point one; the start time point $T_2$ from target point one; and the landing time point $T_3$ on target point two.

The state of the movement is determined by placing all targets and the pen tip together in one electronic circuit. When the pen tip $P_{tip}$ makes electrical contact with one of the targets a part of the electronic circuit is short-circuited. This way a different state of the pen results in a different discrete voltage level. Figure 2.2 shows the electronic circuit. The choice of the electronic resistors influences the distinguishable voltage levels. The source voltage is tapped from
the same source that provides the voltage for the Wheatstone-bridges, used in the force transducers. Thus $V_{src} = 2.5 \text{ Volt}$.

Figure 2.3 shows a theoretical time reference signal. In reality the transition between two experimental states is not a clear step. Round the transition points vibrations in the signal can occur. The actual time points are defined as the points, where the pen makes contact with a target for the first time, when landing, or loses contact for the last time, when starting. The procedure to determine the four time points is as follows. First the time points where the pen makes contact with a target point are determined. $T_1$ is the time point where the time reference signal drops below the threshold level of 1.25 $\text{Volt}$ the first time. Next $T_3$ is determined as the point, where the signal drops below 0.75 $\text{Volt}$ the first time. To determine the points where the pen loses contact with the start point or target point 1, the signal is observed backwards. $T_2$ is the point, starting in $T_3$ and looking backwards, where the signal drops below the threshold level of 1.25 $\text{Volt}$ the first time. $T_0$ is determined identically starting in point $T_1$ with a threshold level of 1.75 $\text{Volt}$. The start point has to be determined separately because it does not always correspond with the theoretical start point, the trigger point. In the software routine used to collect the data the trigger point is determined as the voltage crosses the threshold level the first time.

**Landing force**

The force applied on the target by the pen represents the extent of deceleration of the movement. A force transducer measures this impact quantity. The maximum value of the force occurring during the collision represents the landing impact, the extent of deceleration of the movement just prior to landing.
2.2. MEASUREMENT METHODS

Two force transducers measure the applied force on the two goal target points. An U-shaped metal block supports a target point. One end of the U-shape is glued underneath the plateau. The other end of the U-shape ends in a metal strip. The target is attached at the other end of the metal strip. This attachment is a screwed connection. The targets are positioned in a hole in the plateau. The upper surfaces of the target and the plateau are aligned. The plateau is adjustable for the various target sizes. During experimental conditions, contact between plateau and target can occur.

The targets are changed regularly during experiments. A change in tightening of the target on the strip changes the elasticity of the connection. The connection between target and strip is relatively small, compared to the diameter of the large targets. When the pen lands eccentrically on the target bending moments can occur.

The force transducer is positioned on the metal strip. Two strain-gauges are glued on each flat side of the strip. It is only possible to detect applied force parallel to the strain-gauges. This is the vertical direction, perpendicular to the plateau. These strain-gauges are placed in a Wheatstone-bridge. A force on the target point causes strains in the gauges. This results in a change in the resistor values of the gauges, which causes a change in the output voltage. All four gauges are placed in the vertical direction. The bending of a strip does not influence the measurements. However, a changing temperature does affect the measurements. The plateau itself is not infinite stiff. This induces dynamic responses in the strip as a result of the collision.

Both force transducers use the same equipment. All strain-gauges are connected to the type 2B30/2B31 High Performance, economy Strain-gauge /RTD Conditioners (Analog Devices). The neutral resistor of a strain-gauge is 120\(\Omega\). The source voltage of the Wheatstone bridge is generated by a source type 2B35 Precision, Triple Output Transducer Power Supply of Analog Devices. The source voltage is regulated on 2.5\(V\). The maximum deflection of the output voltage of the measure-bridge is 1.0\(V\). This voltage is amplified with a factor 10. The ratio between applied force and outgoing voltage is calibrated, 1\(V\) = 100.2\(N\).

Landing impulse
The change of impulse of the pen during landing can also represent the extent of deceleration of the movement prior to the landing. During the collision the change of impulse of the pen equals the change of impulse of the target. The impulse is assumed to be passed on to the metal strip, through the rigid target point, where the resulting force is measured. The integration of the force signal \(F\), \(\Delta p = \int F\,dt\) gives the change of impulse \(p\) of the target. The landing impulse is defined as the change of impulse caused by the landing of the mass of the pen.

Landing velocity based on landing impact
A more direct parameter to represent the extent of deceleration of the movement prior to landing is the actual landing velocity. If the collision conditions are known, the landing velocity can be calculated from the landing impulse using the impulse equilibrium and the energy equilibrium equations. During collision the movement of the mass of the pen is decelerated from the landing velocity \(v = v_{\text{land}}\) to a standstill of the pen \(v = 0\). The landing velocity is determined from \(\Delta p = m\Delta v\). The assumption is made, that there is no bounce back velocity from the pen. The mass of the pen \(m\) is a constant. This way the impulse level can directly be translated into the landing velocity level, \(v_{\text{land}} = \frac{\Delta p}{m}\).

Landing velocity based on movement accelerations
Another method to measure the landing velocity is to use acceleration transducers. The integration
of the acceleration signal gives the velocity pattern during movement. The landing velocity is the value of the velocity at the point where the pen contacts the target. Integration of the acceleration signal from the start point \( T_0 \) to the landing on target point \( 1 \) \( T_1 \) leaves the landing velocity, if the start velocity was zero.

The acceleration transducers measure directly the acceleration patterns of the pen during movement. The acceleration transducers are positioned on the top of the pen. Two different acceleration indicators using different physical properties are used. The first acceleration transducer uses piezo resistors. This accelerometer will be referred to as the strain-gauge accelerometer. The piezo resistors measure strains, just like normal strain-gauges. Through a Wheatstone-bridge these strains are transferred in a voltage. This voltage is a measure for the actual acceleration in the specified direction. This meter is more appropriate to measure signals that have frequencies with low contents (0 – 600 Hz) and a small acceleration range (±10g). It is possible to measure the influence of gravity (1 g). This measure is equipped to measure two acceleration signals in two perpendicular directions simultaneously. This way the whole two dimensional movement can be followed. The positive orientation of the vertical axis lies reversed to the direction of gravity. The horizontal axis lies in line with the three targets. It is positively orientated from \( P_0 \) to \( P_1 \). The measurements in vertical direction are corrected for the influence of gravity. When the pen stands still no accelerations are measured.

The second acceleration transducer uses piezo electronical material. This indicator is of the type PCB 303A02. This acceleration indicator has a range of ±500g with a sensitivity of 10mV/g, and a frequency range (±5%) of 1 – 10000Hz. This accelerometer will be referred to as the piezo accelerometer. This transducer is more appropriate to measure accelerations during the collision phase of the experiment. This acceleration meter can only be used in one direction. It is used in the vertical direction parallel to the measuring axis of the force indicators.

Figure 2.4 shows the position and orientation of the different transducers. The two force transducers are positioned underneath the two target points. Strain-gauges are glued on the target support. At the pen top one of the acceleration transducers is positioned. It is not possible to use both
accelerometers in the same experiment.

2.2.3 Hardware; A/D conversion

To make all measured signals appropriate for operation and interpretation in a software environment, the measured analogue voltage signals are sampled and digitised. Both the used hardware, to convert the signals, and software, to process them, are part of the National Instrument package. The Data Acquisition (DAQ) board samples the data and offers it to a computer. The used DAQ board AT-2150-C+ has 4 input channels. The input resolution of the DAQ board is 16 Bit. The input voltage range of the DAQ board is limited to ±2.82 Volt. During experiments 5 different signals are available. One has to chose which channels to use during which experiments.

The sample rate and the time period collecting the data are identical for all sampled signals. Before sampling all signals are filtered electronically. The low-pass cut-off frequency is the half of the used sample frequency. The input channels are not sampled exactly simultaneously. The channel rate, with which the channels are sampled, is the sample rate multiplied by the number of channels. The period, in which all channels are sampled once, is distributed equidistantly in as many periods as there are sampled channels.

2.2.4 Software

The software to process the data is written in Labview. Labview routines are designed for data acquisition and instrument control. The programming language is especially equipped for data processing. Labview contains special routines for data analysis, data presentation, and data storage. Most programs use text-based languages. Labview however uses a graphical programming language, G, to create programs in block diagram form. A Labview program is called a virtual instrument (VI). This because its appearance and its operation imitate actual instruments.

As well as general programs, Labview has an interactive user interface and a source code equivalent. The interactive user interface is called the front panel, because it simulates the panel of a physical instrument. The program receives its instructions from a block diagram, that is constructed in G. The block diagram is the source code for the VI.

VIs are hierarchical and modular. Every independent program can be used as a main program as well as a sub routine within other programs.

To perform the experiments by van Loon, see Section 2.3.4, a Labview program, target.vi, is written. In this program the four sampled data signals (time reference, force, acceleration in z-direction, and acceleration in x-direction) are processed into the characteristic parameters (MT1, DT, MT2, Fmax, Δvimpulse, and Δvacceleration). Accept for the velocity step based on impulse all parameters can be read directly from the front panel. The velocity step based on impulse has to be read from the graph impulse against time during the first collision period, on the front panel. The determination of this parameter is not detectable for all experiments. It can not be written in a robust software routine.

Appendix D shows the front panel and the corresponding block diagram of the written software routines. The main program, target.vi processes characteristic parameters from the four data signals. This program is built up from standard Labview VIs and a few new written VIs.

The data input.vi is a modification of a standard data input VI. This VI controls the actions of the DAQ-board. It tells the data processor: what DAQ-board to use; which channels to sample; with what sample rate; how many data points to obtain; and under which trigger conditions to start the data acquisition during an experiment. The main result is a two dimensional array, that contains four channels times the number of data points.
The separate 4 channels.vi separates the two dimensional array in four one dimensional arrays, that contains the four measured signals.

The four time points are determined in timepoints.vi. This routine compares the time reference channel with the threshold level as described in Section 2.2.2. The four time points are the output.

The threshold level.vi performs the actual comparison. Here an array starting at a certain array point is followed and the array point, where the defined threshold level is crossed, is determined. This array point is the output.

The mean signal part.vi is used, to compensate hysteresis errors in the force signal. This signal is corrected with the mean of the unaffected force signal. This mean value is determined from the first part of the force signal, the period before the pen contacts target one. This routine can also be used to check the correct gauging values of the acceleration signals.

Although Labview has its own numerical integration routine, an extra routine, integrator.vi routine is written. The original Labview routine calculates the total integration value of a signal between two integration boundaries. The new integration routine supplies the integration value for every sample during the integration period. The new Labview routine is described with the discrete numerical integration function:

\[ I_k = \sum_{j=0}^{k} \frac{1}{4} \Delta h(F_{j-1} + F_j + F_{j+1}) \quad \forall \quad k \epsilon [0, N - 1] \]  

\[ F \quad : \quad \text{Function value} \]
\[ I \quad : \quad \text{Integration value} \]
\[ k, j \quad : \quad \text{Array indices} \]
\[ \Delta h \quad : \quad \text{Integration step} \]
\[ N \quad : \quad \text{Array length} \]

The velocity step during movement and the impulse during collision are determined by integration of the acceleration in z-direction and the force signal.
2.3 Analysis

2.3.1 Sample rate

The sample frequency is one of the experimental conditions that has to be determined. As a result of the use of a low-pass filter, a low sample rate causes loss of higher frequency signal contents. One wants to measure every signal with a sample rate high enough to maintain all important information. On the other hand an infinite high sample rate results in an enormous amount of data. This can cause problems during the data collecting and processing. For every data signal the optimum is investigated, where the data is measured accurately with the smallest possible sample rate. As all data signals are sampled simultaneously, the actual sample rate is restrained to the sample rate of the signal that requires the highest sample rate. One has to bear in mind that, by using the AT-2150-C+ DAQ board the minimum sample rate is limited to $f_{sam} = 4kHz$.

The optimum sample rate depends on the accuracy requirements. From experiences of previous experiments the researchers have a clear view on the accuracy demands. The movement and dwell times have to be determined within an accuracy range of $\pm 1.0msec$.

The use of impact parameters is rather new in this research field. In this case no specific limitations are stated. The researchers post process the data of the experiment statistically. The accuracy of the research is influenced strongly by the use of human subjects that causes a significant spread of the data. The statistical research requires a relative accuracy of the parameters of $5-10\%$.

The accuracy of the determination of the time points, necessary to determine movement and dwell times, is verified while using the minimum sample rate of $f_{sam} = 4kHz$. The time points, that represent the transition of an experimental state, are not measured at the exact time point. This because the time points are measured at the point where the time reference signal crosses a threshold level. This threshold level differs from the state voltage. The actual time point is defined as the point where the state of the experiment changes, thus the voltage level changes. The time points $T_1$ and $T_3$ are measured a step to late. The magnitude of the period, that the time points are measured inaccurately, depends on: the voltage step of the signal; the filter frequency; and the voltage divergence between the threshold levels and the state voltage levels.

In theory the time reference signal consists of several step signals. The frequency range of such signals is in theory infinite wide.

The errors between measured and actual time points are observed from experimental results. Table 2.1 gives these observations, along with the voltage steps corresponding with these transition points. The low pass cut-off frequency is $f_{fil} = 2kHz$. The accuracy range of the measured time points is the result of the sample frequency $f_{sam} = 4kHz$.

<table>
<thead>
<tr>
<th>Time point</th>
<th>Measured time point</th>
<th>Transition step</th>
<th>Threshold level divergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>$t_0 \pm 0.25msec$</td>
<td>+0.5Volts</td>
<td>+0.25Volts</td>
</tr>
<tr>
<td>$T_1$</td>
<td>$t_1 - 0.25 \pm 0.25msec$</td>
<td>-1.0Volts</td>
<td>-0.75Volts</td>
</tr>
<tr>
<td>$T_2$</td>
<td>$t_2 \pm 0.25msec$</td>
<td>+1.0Volts</td>
<td>+0.25Volts</td>
</tr>
<tr>
<td>$T_3$</td>
<td>$t_3 - 0.50 \pm 0.25msec$</td>
<td>-1.5Volts</td>
<td>-1.25Volts</td>
</tr>
</tbody>
</table>

The movement times are determined by subtracting two time points. In case of movement time 2, $MT_2 = T_3 - T_2 = t_3 - t_2 - 0.50 \pm 0.50$. The accuracy range is overestimated. For an 95\% accuracy interval the range is limited to $\pm 0.25\sqrt{2}$. This means that when the movement times are corrected
with the specified value, $+0.50$ in case of $MT_2$, the accuracy requirements are satisfied.

The maximum force is measured as the maximum value of the force peak, see Figure 2.8. The force peak has high frequency contents, this requires a high sample rate to prevent information loss. The power spectra (Figure 2.5) of two force signals, that are the result of two experiments using the original and the damped pen, show the frequency range within which the majority of the signal is measured. The signals are sampled with $f_{sam} = 32 kHz$. For means of visibility the square root of the power spectrum amplitude is plotted, this is identical to the absolute value of the FFT of the signal. Figure 2.6 shows the percentage of the signal contents as a function of the frequency. In this plot it is possible to determine a threshold within which the frequency range contains accurate data to represent the signal accurately enough. A signal contents of 95% can be obtained for the damped pen in a range of $0 - 2kHz$, thus requiring a sample rate of $f_{sam} = 4kHz$. For the original pen this range is $0 - 4kHz$, resulting in $f_{sam} = 8kHz$.

![Figure 2.5](image1.png)  
![Figure 2.6](image2.png)

Figure 2.5: The power spectra of two force signals, obtained as a result of two experiments using the damped (-) and the original pen (-). For means of visibility, the square root of the amplitude is plotted, this is the absolute value of the FFT response of the signal.

Figure 2.6: The percentage of the signal contents as a function of the frequency range. The signal contents is determined for two force signals, as a result of the use of the damped (-) and the original pen (-).

The actual effect of the sample rate on the result of the maximum force is determined in Appendix A. The used signals are the result of a drop test. The pen is dropped from a height of $15cm$ on the target. The signal is measured with a sample rate of $32 kHz$. The results of $4$, $8$, and $16 kHz$ sampling are simulated by post processing this signal. The results of the maximum force values show that a sample rate higher than $16 kHz$ is required. The use of the damped pen does not show an improvement to the use of the original pen.

Although the impulse level is directly derived from the force signal, the impulse level can be determined more accurately with a smaller sample rate. This value is identically determined as for the required maximum force value sample rate, see Appendix A. To measure the impulse level accurately a sample rate of $4 kHz$ is sufficient. The use of the original pen, compared to the damped pen, shows a better result, but both pens can be used.

The acceleration transducers are primarily used to measure the movement phase of the experiment. The acceleration patterns during this phase do not contain frequency contents bigger
than 2kHz. Therefore the minimum sample rate of 4kHz is sufficiently large. In case when the acceleration transducers measure the data during the collision phase of the experiment, identical considerations are valid as in case of use of the force transducers. The operation range of the strain-gauge acceleration transducers is limited till 0 - 600Hz.

The loss of information of the impact quantities using a sample rate of \( f_{\text{sam}} = 4kHz \) is acceptable, accept for the landing force. In order to comply with the maximum force requirements, the costs to process the data are strongly increased.

### 2.3.2 Movement times

**Time reference signal**

Figure 2.7 shows the result of a measured time reference signal. The signal is the result of a two-step experiment using large targets sampled with 4 kHz. The step of the voltage levels at the transition points is practically not as clear as expected. Instead of a clear single step vibrations are noticed.

![Figure 2.7: The time reference signal. The dashed lines distinguish the transition time points \( T_0 - T_3 \).](image)

The fluctuations are stronger at the landing points, \( T_1 \) & \( T_3 \), than at the starting points, \( T_0 \) & \( T_2 \). The fluctuations at the transition pointed are closer investigated in Appendix B. At the landing point, the vibrations are multiple. The time period of these vibrations can last up to 50msec. At the starting point the number of fluctuations varies from 0 to 2. When multiple fluctuations occur, they continue up to 10msec maximum. The occurring collision causes the vibrations at the landing point. The metal stylus that lands on the metal target does not stand still immediately, but bounces. At all four transition points the influence of the elasticity of the plateau and its support is noticeable. A sudden change in force causes vibrations in the plateau and its support. Due to these vibrations the contact between target and pen is disturbed.

### 2.3.3 Impact parameters

**Force signal**

Figure 2.8 shows a representative force signal taken from a two step, big targets experiment. All
measured signals shown in this Section Analysis, if not noted otherwise, are taken from the same experiment. The force signal shows a narrow force peak with a following side. In the force signal, only force is applied during the dwell time, the period the pen makes contact with the target. Looking closer at the force signal, see Figure 2.9, a force-less period can be noticed just after the force peak. After this period force is applied continuously until the pen loses contact. At the point where the pen makes contact with the second target point $T_3$, fluctuations can be noticed in the force signal of the first target point.

The force signal is a result of the pen colliding on the target, followed by the stabilisation of the arm and the hand holding the pen. The collision of the metal pen on the metal target causes the narrow force peak. As a result of the collision the pen bounces back. The following hand and arm push the pen back on the target, which causes the following side in the force signal. The pushing of the hand on the target is a result of the deceleration of the movement velocity of the hand and stabilisation of the hand. The skin between the fingers and the pen delays the influence of the hand and arm. During the force-less period, the bounce back force of the collision is stronger than the pressure applied by the hand. The force-less period is also noticeable in the time reference signal. During this period the contact between pen and target is lost, see Figure 2.12.

The impulse step is the integration of the force peak (Figure 2.10). This impulse step, caused by the force peak, is detectable during the force-less period. During this period the impulse level remains constant. This level is clearly detectable in the impulse signal, Figure 2.11. The impulse level is detectable in over 90% of the experiments. When the level is not detectable there is no force-less period. This can be caused by a bad contact during collision or a solid grip of the hand, this causes immediate pressure big enough to prevent bounce back.
2.3. ANALYSIS

Figure 2.10: The force signal during the first collision period (8 msec after $T_1$). After the force peak a force less period is noticeable.

Figure 2.11: The impulse signal during the first collision period. The force less period results in a constant impulse level during that period.

Figure 2.12: The time reference signal during the first collision period. During the force less period, the contact between pen and target is lost.

Acceleration signals
The landing velocity based on the acceleration behaviour is calculated from the data generated by the strain-gauge transducers. Figures 2.13 & 2.14 show acceleration patterns in z- and x-direction of the experiment.

Figure 2.13: Acceleration pattern using the strain-gauge acceleration transducer in z-direction. The movement of the pen can be derived from the patterns during the movement periods $MT_i$, between $T_0$ & $T_1$ and $T_2$ & $T_3$.

Figure 2.14: Acceleration pattern using the strain-gauge acceleration transducer in x-direction.

The period before $T_0$, the z-acceleration signal shows the standstill of the pen. The x-acceleration signal however shows continuous fluctuations during this period. The start of the movement, at $T_0$ can cause signal fluctuations with high frequent contents. These peaks at the start of the movement can occur in both signals. During the movement period continuous, homogeneous signals are recorded. The acceleration patterns show cycles of increasing and decreasing acceleration and
deceleration of the movement. The collision with the target causes high frequent, large amplitude accelerations. The acceleration range that can be measured, is limited due to the voltage input range of the DAQ-board. $V_{lim} = \pm 2.82$ Volt $\equiv a_{lim} = \pm 13.8 m/s^2$. The frequency range of the strain-gauge acceleration transducer is limited to $f = 0 - 600 Hz$. Therefore the collision response can not be measured. After the first collision period the signal in z-direction shows a damped harmonic signal. The x-acceleration signal shows continuous fluctuations during this period. The acceleration behaviour of the second movement step is analogue to the first movement step.

The velocity step is the integration of the z-acceleration signal between $T_0$ and $T_1$. Kinematic knowledge of the position behaviour is used, to gain insight in the accuracy of the calculation of the velocity step. The position signal, $u$, can be obtained by two integration steps of the acceleration signal. The start value of the velocity is known $u_0 = 0$, the end value is the desired characteristic parameter $v_1 = v_{land}$. Both the start and the end position of the movement are known, $u_0 = u_1 = 0$. The position is limited by the plateau, the position can not become negative.

Calculating the end position value, this value lies in a range of $u_{land} = \pm 20 mm$. This is a large error as the maximum deflection in z-direction is $u_{max} = 30 \text{mm}$. Several sources cause errors in the acceleration signal, and subsequently in the calculated landing velocity and position. The calibration of the strain gauge accelerometer lies within a certain accuracy range. The here induced error generates a continuous divergence in the acceleration signal. This causes a linear increasing error in the velocity signal, and a quadratic increasing error in the position signal.

Measurements of an unaffected signal show a 'normal' distributed spread of the data. The standard deviation of the spread of this signal is $\sigma = 1.1 * 10^{-2} [m/s^2]$. Integration of this signal leaves a damped noise signal. Further integration steps decrease this error.

Transition point vibrations at the start point are another error source. When the start time point is not measured at the correct point, the start conditions are not correctly observed. When the colliding effects influence the start of the movement, a sharp high frequent peak can be observed at the start point. These effects leave errors in the acceleration signal at the start point. This causes a continuous error in the velocity signal, and a linear increasing error in the position signal.

The acceleration transducer is positioned at the top of the pen. As a human being holds the pen during experiments, the orientation of the pen is not correct and changes all the time. During the experiment the pen has a rotation point round the y-axis. The y-axis is perpendicular to the x- and the z-axis (orthogonal). During movement the pen can rotate round the grip of the hand. During contact with a target point the pen rotates round the pen tip. In z-direction, gravity influences the acceleration signal. The orientation angle error can cause a static and a dynamic error in the acceleration measurements. The subject causes the static error, as the pen is not hold exactly vertical in the gravity field. In this case the gravity component is measured to small. An orientation angle error of $8^\circ$ means that the transducer in z-direction measures still $99\%$ of the actual behaviour. An error of $18^\circ$ results in a $95\%$ correct signal. A subject is likely to stay within the $18^\circ$ range.

During the experiment the orientation angle changes round the z- and y-axis, especially at the transition points. A change in the slope causes rotational accelerations in the pen. These induced accelerations affect the measurements of the x-component. An indication of the influence of this dynamic error in the velocity behaviour can be shown by measuring the accelerations during movement time 1 in y-direction. The movement is two dimensional, so no y component of the acceleration is expected. Figures 2.15 & 2.16 show the acceleration component of the y- and x-direction for two identical one step large target experiments. The acceleration range in y-direction is from the same magnitude order as the acceleration range in x-direction. The y-component is a
100 % error. So the dynamic orientation error makes the x-acceleration pattern unsuited to process accurate parameters.

Figure 2.15: The x-component of the acceleration pattern between $T_0$ and $T_1$ of a two step, large target experiment.

Figure 2.16: The y-component of the acceleration pattern between $T_0$ and $T_1$ of a two step, large target experiment. No fluctuations in y-direction were expected as a result of the two dimensional movement in the z-x plane.

The same error source that generates the significant position error can cause an acceptable error in the result of the velocity step. This because a certain type of error in the acceleration signal causes a certain order error propagation in the velocity signal, causing an error in the landing velocity. As the position signal is integrated from the velocity signal, the error propagation order in the position signal is a step increased. Thus a continuous error in the velocity signal causes a linear increase of the error in the position signal. This is specified for two error source, in case of a transition error occurring in the acceleration signal at the start point of the movement, $T_0$, and in case of a calibrating, gauging error of the acceleration signal in z-direction. Figures 2.17, 2.18, and 2.19 show the original acceleration, velocity, and position signal between $T_0$ and $T_1$. The position signal shows a significant error of the landing position, $u_{land} = 9.5\text{mm}$. The transition error is assumed to be caused only by the fluctuations in the acceleration signals at the start point $T_0$. A theoretical error in the first acceleration sample represents this fluctuation. In reality fluctuation peaks, that last approximately 10 $\text{msec}$, can be noticed. A single pulse at the first point of the acceleration signal causes a continuous difference in the velocity signal, and a linear increasing divergence in the position signal. Figure 2.20 shows the divergence in position signal necessary to compensate the error in the position signal at the landing point. This error is known from the kinematic conditions $u_{land} = 0$. The Figures 2.21 & 2.22 show the effect on the velocity signal and the position signal of the correct compensation of the error in the first acceleration pulse.
In this case a single error pulse of $a_{\text{error}} = 1.2 \times 10^2 m/s^2$ of the first sample results in a continuous error in the velocity signal of $v_{\text{error}} = 0.029 m/s$, and a linearly increasing error in the position signal till $v_{\text{land}} = 9.5 mm$. This first sample divergence is not realistic. However the negative fluctuation 12.5 msec pattern occurring just after $T_0$ generates a 5.5 mm divergence at the landing point, and a 0.017 m/s divergence in the landing velocity.

Gauging errors cause a constant divergence in the acceleration signal. This error is processed in a linear increasing error in the velocity signal, and a quadratic increasing error in the position signal. Figure 2.23 shows the quadratic position pattern to compensate the position signal, so that the kinematic landing condition is fulfilled. Figures 2.24 & 2.25 show the results of the compensation of the gauging error on the velocity and the position signal. The velocity signal is compensated with a linear increasing pattern.
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Figure 2.23: The assumed quadratic increasing error in the position signal.

Figure 2.24: The velocity signal corrected with the quadratic error increasing in the position signal.

Figure 2.25: The position signal corrected with the quadratic increasing error.

A gauging error of $a_{\text{error}} = 0.17m/s^2$ should cause the error in the landing position of $u_{\text{land}} = 9.5mm$. This results in an error of $v_{\text{error}} = 0.054m/s$ in the landing velocity value. The actual gauging error for this measurement is estimated on $a_{\text{error}} = 0.05m/s^2$. This results in an error in the landing position of $u_{\text{land}} = 3.1mm$ and an error in the landing velocity of $v_{\text{error}} = 0.017m/s$. However, the static orientation angle error can cause only errors in one direction. This is also a type of a gauging error.

It seems that all error sources cause a part of the divergence in the landing condition. The results of the two calculated error sources do not explain the total measured landing value. They explain $\frac{5.5mm + 3.1mm}{9.8mm} = 88\%$. Both sources generate an error in the landing velocity of $v_{\text{error}} = 0.017 + 0.017 = 0.034m/s$. Assuming that this is also 88% of the total error, than the total error would be $v_{\text{error}} = 0.038m/s$. On a measured landing velocity of $v_{\text{land}} = 0.43m/s$, the relative error in this velocity measurements is 8.8%. This error propagation is calculated for a single measurement representing the performed experiments. No reproducible measurement setup is developed and no statistical analysis is performed on the results. Therefore, no concrete conclusions can be drawn from the above calculated error propagation. It can only be used to indicate that the relative error for the determination of the landing velocity based on acceleration patterns lays round the 10% range.

The signal in x-direction is not useable, to draw numerical quantified results. These signals can be used for general observations. During movement, acceleration patterns caused by control actions can be noticed. This is a direct link to the control behaviour, but at this point it is not clear how to characterise the patterns. So far only the numbers of acceleration deceleration cycles are counted to represent the number of control cycles, as done by Adam et al. [6].

2.3.4 Kinesiological experiment by Van Loon

A kinesiological experiment is already carried out with this experimental setup, Van Loon & Adams [2]. The aim of this research was to investigate the effect on the target impact as a result of the one-target advantage. For every experimental run the impact quantities and the movement times were measured. Six experimental conditions are used: two movement types, one and two step; three target magnitudes, large, medium, and small. The twelve(12) subjects had to repeat every condition ten times. Table 2.2 shows the measured values, averaged over all experimental runs, of
the characterising parameters.

Table 2.2: Experimental results

<table>
<thead>
<tr>
<th>Movement</th>
<th>one step</th>
<th>two step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target size</td>
<td>small</td>
<td>medium</td>
</tr>
<tr>
<td>$MT_1$ (msec)</td>
<td>584</td>
<td>473</td>
</tr>
<tr>
<td>$DT$ (msec)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$MT_2$ (msec)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$F_{max}$ (N)</td>
<td>46.7</td>
<td>61.7</td>
</tr>
<tr>
<td>$\Delta v_{impulse}$ (m/s)</td>
<td>0.26</td>
<td>0.39</td>
</tr>
<tr>
<td>$\Delta v_{acceleration}$ (m/s)</td>
<td>0.24</td>
<td>0.29</td>
</tr>
</tbody>
</table>

The results show decreasing movement times and increasing impact quantities for increasing target sizes. The more complex two step movement, compared to the one step movement, shows increasing movement times. Statistical research does not detect the effect of the one or two step movement in the results of the impact quantities. Therefore the investigated target impact constraint hypothesis was not upheld by this experiment.

Id. the results shown in table 2.2 are not exactly identical to the experimental result described by van Loon & Adam. The here measured results do use all measurements, including the results of subjects that show a large divergence in movement performance. The conclusions of the investigation remain the same.

2.3.5 Experiments performed by Teasdale & Schmidt

Teasdale & Schmidt [1] conducted an experiment to investigate the correlation between movement speed and landing impact. Most experiments in this research field model the control behaviour based on the movement constraints velocity and accuracy. This behaviour depends on the visual feedback and the variability of the muscular system. Teasdale & Schmidt performed experiments without varying the accuracy demands. The subjects were asked to perform a movement within a certain time period or with a certain landing force. They concluded that the impact with a target is an important contribution to the deceleration of the moving limb and a critical determinant of movement organisation.

Performing the experiment a subject had to conduct a single step movement in the anterior-posterior plane. The apparatus was constructed in such manner that the movements in the medial-lateral and inferior-superior plane were negligible. The hand moved a stylus on to a target in front of him. The accelerations during movement, the landing force, and the movement time were used.

A lever construction was build so that three potentiometers could record the three dimensional movement of the pen, two translational movements and one rotational movement. With the use of simple trigonometric functions the potentiometer signals were translated in three dimensional Cartesian displacement co-ordinates. The displacement signals were numerically differentiated twice to obtain the acceleration signals.

The force was measured by strain-gauges positioned on the handle. The strain-gauges were build in a simple DC Wheatstone bridge.

The movement times were measured between the moment of movement initiation and the moment of the sharp upswing of the impact-time curve. Movement initiation was measured by an
2.4. DISCUSSION

Electrical conducting circuit, that send a voltage pulse when initial contact at the start point was lost.

All signals were digitised with a sample frequency of $f_{sam} = 250\text{Hz}$. The signals from the potentiometers were filtered with fourth-order zero-phase shift filter with a cut-off frequency of $6.4\text{Hz}$.

The experimental conditions are not described completely. Considering the problems occurring with the determination of the maximum force in the goal directed movement with collision experiment, one has to question the validity of the value of the maximum force in this experiment. The material properties and the exact position of the force transducer are not specified. The use of a sample rate of $f_{sam} = 250\text{Hz}$ will probably cause a big amount of signal loss. The dynamics of the system seem to cause fewer problems in this experimental measurement setup.

2.4 Discussion

2.4.1 Movement and dwell times

The calculation of the movement times based on the time transitions points self is accurate enough. However the periods of the fluctuations of the time reference signal around the transition points require further attention. The calculation of the movement times is based on the first contact of the pen with the target when landing and the last contact when leaving a target. If this assumption is not correct, the fluctuation periods cause significant errors in the movement time calculation.

The fluctuations noticed in the time reference signal occur between the two voltage levels matching that particular transition. If the fluctuations were caused by influences of the time dependent behaviour of the electrical circuit or the filter procedure, the range of the expected fluctuations would not lie exactly between the two levels. Because the fluctuations occur between the two levels, they seem to be the result of the contact loss, it looks like a bad contact in the electrical conducting circuit. This is caused by bouncing between pen and target.

The vibrations at the landing points are caused by back bounces, after the metal metal collision and by extra vibrations of the pen and the target. These extra vibrations are the result of the dynamic response of the supports of both colliding objects, the hand and the plateau. Vibrations occurring at the point where contact is lost, are caused by dynamic influences caused by the take off force step of the movement. It is also possible, that during the horizontal movement just after the take off one has not gained enough height, so that an extra short contact occurs at the starting point. The risk that this phenomenon occurs is most likely at the large target points.

Technologically the assumption, to determine the time transition points at the point of first contact when landing and the last contact when leaving, seems correct. Physiologically this assumption requires further discussion. Especially the dwell time, which is physiologically determined as the period the pen makes contact with the target. Kinesiologically it is the period, where the position of the hand is stabilised and in case of a second movement this movement is prepared.

2.4.2 Maximum force

At this moment force is used to measure the target impact. One could consider to measure the impulse or energy of the pen during experiments. The amount of energy or impulse left just prior to landing, the amount lost during landing, and their difference could provide interesting information. In this experiment only the vertical component of a predominant horizontal movement is measured. The landing impact is characterised by $F_{max}$, the maximum value of the force caused by the impact
of the pen on the target. The influence of the hand and arm on the force is difficult to separate form the force signal.

Technologically the force transducers are not suited to measure the maximum force value. To measure the force peak accurately, a high sample rate is required. To measure the following hand force accurately the signal noise is too big. The strain-gauges measure strains in the metal strip, that represent the force applied on the target. However dynamic responses induced at the transition points cause further strains in the strain-gauges. The different parts of the target point support have masses and their connections are not infinite stiff. The force necessary to start the movement is partially gained from a take-off of the start point. The landing is a collision between two metal objects supported by their own supports. Both phenomena cause responses in the strain-gauges. The applied force is transduced by the target into the metal strip. The connection between these two parts is not identical for various experiments. This is a result of the target changes between experiments.

2.4.3 Landing velocity based on landing impulse

Like the maximum force, the landing velocity based on landing impulse represents the impact, the change of impulse during collision. The landing velocity is processed from the force signal. During this process two assumptions are made. First, the impulse signal, the integration from the force signal is determined. This signal shows a more consistent result then the force signal itself for the used sample rate. This process step is based on \( p = \int F dt \). However the collision does not only excite the target but also the different support parts. The elasticity of the experimental construction influences the result of the impulse equation.

Second, the landing velocity is processed from the impulse signal. This is done using the equation, \( v_{\text{land}} = \frac{p}{m} \). Here is assumed that there is no outgoing, bounce back velocity of the pen. However this bounce back does occur. The magnitude of the bounce back is unknown. The piezo acceleration transducer could supply this information.

2.4.4 Landing velocity based on movement accelerations

The landing velocity determined from the acceleration signals seems to be determined by a more accurate processing method. However several error sources effect the acceleration signal in z-direction during the movement period and influence the result of the landing velocity. The gauging error, the fluctuations at the start point, and the static orientation angle error effect the result. The influence of these errors are estimated to stay within the 10% accuracy range. This finding however is not based on statistical or reproducible research, but only on several independent observations.

2.4.5 Comparison experimental velocity results

Landing velocity based on two methods is calculated during experiments. Comparing these results it shows, that the use of small targets generates comparable velocity results. For increasing targets, the landing velocity based on landing impulse increases faster. Bigger differences between the results of the two methods are noticeable.

The outgoing, bounce back velocity of the impulse method explains this difference partially. A bigger landing velocity causes a bigger bounce back velocity. These two velocity components together are added in the landing velocity based on impulse. As the collision conditions are not known and are changed during experiments, the bounce back velocity is unknown. The magnitude of the bounce back velocity depends on the actual landing velocity, but the relation between the
two depends on the impulse and energy equilibrium equations that describe the collision. However the collision conditions are unknown.

The landing position is not processed from the acceleration signals during the performed experiments. Therefore there is no indication for the magnitude and direction of the error in the velocity signal based on acceleration patterns.

2.5 Conclusions and recommendations

2.5.1 Conclusions

- The movement times $MT$ and $DT$ in the here presented form can be measured accurately. It requires discussion on the exact kinesiological definition of the movement and dwell, stand still periods during the experiments. Interpretation of the movement and stand still, dwell periods during the experiment. The exact position of the transition time points have to be defined.

- With this experimental setup it is not possible to measure the maximum force within the accuracy range. The force signal is influenced by the dynamic responses of the support parts caused by the collision. It requires discussion what impact quantity is the most suited to represent the target impact.

- The impulse step derived from the force signal provides consistent results for the used sample rate. However impulse is derived from the inaccurate force signal.

- The landing velocity based on impulse is another property to characterise the landing impact. The landing velocity is derived via the impulse from the inaccurate force signal. Furthermore the calculation of this value is based on the assumption, that there is no bounce back velocity. However this bounce back does occur.

- The landing velocity based on acceleration in $z$-direction is measurable within the 10% accuracy range.

- As long as the acceleration transducer is used at the top of the pen, the acceleration signal in $x$-direction can not be used to quantify numerically experimental properties. This signal can only be used to indicate number of control cycles.

2.5.2 Recommendations

- It requires discussion what properties are to be measured to represent the target impact. Instead of the target impact, it could be interesting to describe the change in energy or impulse contents of the pen during movement and collision.

- At this point only $z$-components of a two dimensional movement, predominantly orientated in $x$-direction, are measured. It is preferable to design a measurement setup, that measures components in $x$-direction. One could consider an one dimensional movement experiment. This however provides designing problems as one has to able to make a two step movement and measure collision properties.

- If the landing velocity is used to represent the landing impact, it is recommendable to adjust the position of the acceleration transducers. This to prevent the influence of the lever effects.
in the acceleration signals, so that beside the z-component also the x-component can be measured accurately. A position at the pen tip, with a small distance between pen tip and hand grip would improve the results.

- If there is a more clear view of the error sources and error propagation in the acceleration signal, it is interesting to process the landing position as well. If it is possible to determine a relation between the magnitude of the error in the landing position and the error in the landing velocity. The measured error in the landing position could be used to improve the result of the landing velocity.
2.6 Nomenclature

The following signs and abbreviations are used in this chapter "Goal directed movements with collision".

**Roman characters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a(t))</td>
<td>Acceleration signal of the pen in vertical direction</td>
<td>(\text{m/s}^2)</td>
</tr>
<tr>
<td>(a_{\text{error}})</td>
<td>Error in the acceleration signal</td>
<td>(\text{m/s}^2)</td>
</tr>
<tr>
<td>(a_{\text{lim}})</td>
<td>Limits of the acceleration DAQ-board input</td>
<td>(\text{m/s}^2)</td>
</tr>
<tr>
<td>(f)</td>
<td>Frequency range of the acceleration transducer</td>
<td>(\text{Hz})</td>
</tr>
<tr>
<td>(f_{\text{sam}})</td>
<td>Sample frequency</td>
<td>(\text{Hz})</td>
</tr>
<tr>
<td>(f_{\text{fil}})</td>
<td>Filter frequency</td>
<td>(\text{Hz})</td>
</tr>
<tr>
<td>(g)</td>
<td>Gravity constant</td>
<td>(\text{m/s}^2)</td>
</tr>
<tr>
<td>(\Delta h)</td>
<td>Integration time step</td>
<td>(s)</td>
</tr>
<tr>
<td>(j)</td>
<td>Array index</td>
<td>-</td>
</tr>
<tr>
<td>(k)</td>
<td>Array index</td>
<td>-</td>
</tr>
<tr>
<td>(m)</td>
<td>Mass of the pen</td>
<td>(\text{kg})</td>
</tr>
<tr>
<td>(p)</td>
<td>Impulse at target point one</td>
<td>(\text{Ns})</td>
</tr>
<tr>
<td>(t_0)</td>
<td>Measured time point of the movement start</td>
<td>(s)</td>
</tr>
<tr>
<td>(t_1)</td>
<td>Measured time point of the landing point on target point one</td>
<td>(s)</td>
</tr>
<tr>
<td>(t_2)</td>
<td>Measured time point of the movement restart from target point one</td>
<td>(s)</td>
</tr>
<tr>
<td>(t_3)</td>
<td>Measured time point of the landing point on target point two</td>
<td>(s)</td>
</tr>
<tr>
<td>(u(t))</td>
<td>Position signal of the pen in vertical direction</td>
<td>(\text{m})</td>
</tr>
<tr>
<td>(u_0)</td>
<td>Position value at (T_0)</td>
<td>(\text{m})</td>
</tr>
<tr>
<td>(u_1)</td>
<td>Position value at (T_1)</td>
<td>(\text{m})</td>
</tr>
<tr>
<td>(u_{\text{land}})</td>
<td>Actual position of landing on target point one</td>
<td>(\text{m})</td>
</tr>
<tr>
<td>(u_{\text{max}})</td>
<td>Maximum deflection of the position signal</td>
<td>(\text{m})</td>
</tr>
<tr>
<td>(v(t))</td>
<td>Velocity in vertical direction</td>
<td>(\text{m/s})</td>
</tr>
<tr>
<td>(v_0)</td>
<td>Velocity value at (T_0)</td>
<td>(\text{m/s})</td>
</tr>
<tr>
<td>(v_1)</td>
<td>Velocity value at (T_1)</td>
<td>(\text{m/s})</td>
</tr>
<tr>
<td>(v_{\text{error}})</td>
<td>Error in the velocity signal</td>
<td>(\text{m/s}^2)</td>
</tr>
<tr>
<td>(v_{\text{land}})</td>
<td>Landing velocity of the pen at (T_1)</td>
<td>(\text{m/s})</td>
</tr>
<tr>
<td>(\Delta v_{\text{acceleration}})</td>
<td>Change of velocity during landing at target point one based on acceleration patterns</td>
<td>(\text{m/s})</td>
</tr>
<tr>
<td>(\Delta v_{\text{impulse}})</td>
<td>Change of velocity during landing at target point one based on landing impulse</td>
<td>(\text{m/s})</td>
</tr>
<tr>
<td>(x)</td>
<td>Orientation, parallel with the plateau from target point one</td>
<td>-</td>
</tr>
<tr>
<td>(y)</td>
<td>Orientation, parallel with the plateau perpendicular to (x) towards the subject</td>
<td>-</td>
</tr>
<tr>
<td>(z)</td>
<td>Orientation, perpendicular to the plateau, opposed to the gravity field</td>
<td>-</td>
</tr>
</tbody>
</table>
DT  Dwell time  \( s \)
\( F(t) \)  Force signal applied on target point one in vertical direction  \( N \)
\( F_{\text{max}} \)  Maximum applied force  \( N \)
\( I \)  Integrated impulse value  \( Ns \)
\( MT_1 \)  Movement time one  \( s \)
\( MT_2 \)  Movement time two  \( s \)
\( N \)  Array length -
\( P_0 \)  Start point -
\( P_1 \)  First target point -
\( P_2 \)  Second target point -
\( P_r \)  Pen state: free in the air -
\( P_{\text{tip}} \)  Pen tip -
\( T_0 \)  Movement start time point  \( s \)
\( T_1 \)  Landing time point on target point one  \( s \)
\( T_2 \)  Movement start time point from target point one  \( s \)
\( T_3 \)  Landing time point on target point two  \( s \)
\( V_{\text{lim}} \)  Input voltage limits of the DAQ-board \( V \)
\( V_{\text{src}} \)  Source voltage \( V \)
\( V_{tr}(t) \)  Time reference voltage signal \( V \)

Greek characters

\( \sigma \)  Standard deviation -
Chapter 3

Rat dynamometer

3.1 Introduction

The rat dynamometer is developed to support research of muscle adaptation and muscle damage. In these research fields one is interested in properties of a single part of the total human movement system. The dynamometer performs fatiguing tests on lower ligament muscles of a rat.

Muscle adaptation research compares the performances of two or more fatiguing tests. Van der Meulen [9] and Kuipers [10] have shown that muscles have adaptive properties. When muscles are loaded to a certain extent, internal adjustments are made. The next time they have to perform these load, they are better prepared and damage is prevented. Muscle damage research investigates the muscle fibres post mortem. When muscles are overloaded, muscle fibres are damaged. One is interested in the types of damage, the damage levels, and the load that causes damage occurrence.

The dynamometer is developed to perform the fatiguing test and measure the muscle performance. The muscles are fatigued by external activation and are forced to follow a prescribed movement. The total fatiguing test is a repetition of muscle activation and movement for a number of times.

Muscle properties are characterised by their elongation behaviour and their force generation behaviour against time. These properties are measured during every experimental repetition. The maximum generated muscle force and the generated muscle work during that experimental run characterise the muscle performance.

The goal of this research is to realise the data acquisition of the experiment and define its operating range. Further, for future developments it is important to gain insight in the actual behaviour of the apparatus and the measurements. An actual development is to measure the actual muscle fibre length instead of the ankle joint rotation, and use it as feedback signal. Before using the measured results, the calibration constants and the system behaviour has to be verified.

This research provides only a first impulse to the work necessary before actual performance of the dynamometer fatiguing experiments. In the rest of this Section the fatiguing experiments are described. The measurement methods and materials necessary to perform the experiment are described in the Section 3.2. The next Section 3.3 contains only a model of the dynamic behaviour of the dynamometer. The Section 3.4 describes the current possibilities to measure the muscle performance and the model relations that have to be verified in gauging experiments.
3.1.1 Dynamometer experiments

Muscle fibres of the rat are fatigued and their performance is registered. The experiments are performed on in vivo, tranquillised rats. The tibialis and gastrocnemius are the lower ligament muscles that are tested. Using the dynamometer two muscle fibres can be tested in two directions. It is possible to use two tibia muscles, agonist and antagonist, and two contraction types, eccentric or concentric contraction. Concentric contraction means that the described muscle elongation lies in the same direction as the stimulated muscle properties. Eccentric contraction is caused by muscle use in the opposed direction of the muscle properties. This load occurs in the tibialis anterior if someone descends a mountain. Here the muscle has to generate force, but is externally elongated.

In this measurement setup the ankle rotation and torque are used to represent the muscle elongation and force of the used muscle. Therefore the knee of the rat is fixed in such manner, that muscle elongation and force only causes rotation and torque round the ankle joint.

The muscle fibres are fatigued by submitting the ankle to a prescribed rotation pattern against time and by stimulating the muscle fibres. Muscle fibres contract or generate force when they are stimulated. Muscle units are activated by a voltage pulse current that runs through the muscle fibres. Normally these the human nervous system generates these voltage pulse currents. The transfer of these electronical currents in contractions is a chemical process. It is also possible to induce these electronical stimulation currents externally. The muscle can be stimulated by placing electrodes on the muscle attachments. An external voltage potential triggers the muscle fibres, to generate force or/and to contract.

Before the start of every fatiguing experiment, the optimum position, the rest length of the muscle is determined. If the muscle is in its rest length it can generate the most force. To determine this optimum, the muscle characteristic force, length curve is determined, see Figure 3.1. In this experimental condition, this curve is translated in an ankle torque, rotation curve, see Figure 3.2. Therefore at several rotation positions, the muscle is stimulated and the generated force is measured. Through these measurement points a fourth order polynomial is fit. The rotation corresponding
3.2. MEASUREMENT METHODS & MATERIALS

with the maximum torque of the curve is the rest length during the actual fatiguing test.

The fatiguing tests consist of a repetition of loads on the muscle fibres. The actual fatiguing experiment starts with a free run. During this run the muscle is not stimulated. This run is necessary to compensate the influence of the inertias of the dynamometer and the rat. The fatiguing experiment self consists of 5 bouts of 80 repetitions. Between every repetition the muscle gets 5 seconds rest and between every bout 20 minutes. Every repetition consists of an enforced rotation pattern of the ankle and during a certain period stimulus of the muscle fibres. The performance of the muscle is calculated for every repetition. For this purpose the results of that particular run and the free run are used.

3.2 Measurement methods & materials

3.2.1 Experimental measurement setup

The rat dynamometer is built in a setup to realise the data acquisition of the experiments. A signal generator produces the set-point signal. The controller generates the motor control current, depending on the set-point signal and the feedback, the actual rotation signal. The dynamometer generates the rotation for the rat ankle joint. The rat generates torques that disturb the prescribed movement patterns. A potentiometer measures the actual movement patterns and provides the feedback of the controller. The motor control current and the actual rotation signals are measured.

Figure 3.3: The experimental measurement setup equipped for data acquisition and processing. The dynamometer provides the rotation for the ankle joint. The influence of the ankle joint of the rat is measured in the response signals. The data acquisition board collects the response signals. A terminal processes the data.
A data acquisition board (DAQ) is used to sample the data. These data signals are processed in to the desired performance parameters, the generated torque and work. The total measurement setup is shown in Figure 3.3.

### 3.2.2 Dynamometer

The rat dynamometer enforces the movement of a rat muscle and measures the muscle performance. A control current controls the motor of the dynamometer, a linear induction motor. A motor induces a force, that causes a part of the motor to perform a translational movement. In the dynamometer this translation is transferred in the rotation, that is applied on the ankle joint.

Because of a more stable behaviour a linear induction motor is chosen, instead of an electro motor, to generate the movement of the dynamometer. In the induction motor the control current generates a Lorenz force with a permanent magnetic field. The force induces a movement of the movable part of the motor. A spinole, a solid metal bar, is positioned on the movable part. This spinole conducts the translational movement in the dynamometer.

![Diagram of the Dynamometer](image)

**Figure 3.4:** The positioning of the spinole by four wheels. The shape of the wheels limits the movement freedom of the spinole to a one dimensional movement. Gravity and friction, caused by the bearings of the wheels, influence the force equilibrium of the spinole.

The transmission in the dynamometer is based on skid less rolling of a wheel over the spinole. The rotation axes, that is connected with the ankle joint, is the centre of the wheel. Four wheels position the spinole. This way the movement of the spinole is limited to a one dimensional movement, see Figure 3.4. One of these four wheels is the transmission wheel. The translation of the motor $x(t)$, is related with the rotation of the rotation axis $\phi(t)$, as $x(t) = r\phi(t)$. $r$ is the radius of the transmission wheel. $\phi(t)$ is used in radians. To prevent skip, the friction between wheel and spinole has to be big enough. Therefore the spinole is clamped between two wheels with a normal force. This force is the result of a spring pushing one of the opposed wheel on the spinole. In theory the spinole can not fall, skid down between the wheels. However after a period of experimental
use, this could occur. To prevent the falling, a small rope is attached between the spinole and the transmission wheel. The stretch of the slope is limited, so that the connection between the spinole and the transmission wheel is always guaranteed. The use of the robe does not affect the transmission behaviour.

The rotation axis is attached to the ankle joint of the rat. The dimensions of the rat are not constant. During ankle rotation, the ankle joint axis moves and its orientation changes a little. To take these discrepancies into account, Beek [3] has developed a special rat foot holder. In this research the influence of the foot holder on the dynamic behaviour of the dynamometer is not taking into account.

### 3.2.3 Control system & set-point generator

The ankle joint has to follow a predetermined movement, a set-point signal. This signal actuates the control system. The control system generates a current, causing a translation of the motor. The translation is transmitted into the desired rotation. Due to the dynamic behaviour of the dynamometer and the rat and the forces generated by the stimulated rat muscles, the generated control current can be inaccurate, to provide the desired ankle rotation. Therefore the actual rotation signal is fed back to the controller and compared to the set-point signal. An electronic PID (Proportional, Integrating, Differentiating) controller adjusts the motor current.

The generated rotation pattern is generated by a special set-point generator. This signal is always of the same form, see Figure 3.5. The range of the rotation (the maximum ($\phi_{max}$) and the minimum ($\phi_{min}$) rotation angle) and the value of the rotation velocity can be adjusted. The rotation velocity with which the first stroke is performed is also adjustable. The back stroke from maximum to minimum level is identical for all experiments. It provides no further information. The rotation starts is always at $t_s = 0.2sec$. The set-point signal is generated by a 16 bit processor. The discrete voltage step is 0.153mV. This corresponds with a smallest angle step of 0.00153°. To generate signals with different slopes ($\alpha$), velocities, the time base in the signal generator is adjusted.

![Figure 3.5: The set-point signal and muscle stimulus, during an experimental run. The set-point signal provides the prescribed rotation for the ankle joint. The stimulus activates the muscle fibres.](image)

An electronical signal stimulates the muscle fibres. The stimulus period is identical for all experi-
mental runs, it lasts $0.4\text{sec}$ and starts at $t = 0\text{sec}$, see Figure 3.5. The signal amplitude has to be big enough to cross the threshold level of the muscle fibres. A bigger amplitude can cause more fibres to contract. The frequency of the stimulus signal influences the activation level of a muscle fibre. Higher frequency causes a bigger activation level, to a certain maximum.

3.2.4 Response signals & muscle performance

To measure the performance of the rat, two signals are measured during every experimental repetition, the actual rotation of the rotation axis and the control current of the motor. These signals are processed into the maximum generated ankle torque and work. A potentiometer measures the actual rotation. This potentiometer is positioned at the centre of the rotation axis. It generates a voltage linearly related to the occurring rotation. Because of the use of the foot holder, the rotation of the rotation axis is not the exact identical rotation of the ankle joint. The motor current is transferred into a voltage by measuring the voltage over a resistor, where the current runs through.

The maximum generated ankle torque is processed from the motor current signal $i(t)$. The motor behaviour can be noted as $F(t) = i(t)B_l$, where $B_l$ is the motor constant and $F(t)$ is the generated motor force. The transmission between motor force and rotation axis torque, $T(t)$ can be noted as $T(t) = rF(t)$, with $r$ the transmission wheel radius. This is the transmission constant. The measured motor current is linearly related to the ankle generated torque. However the force equilibrium is also influenced by: the gravity of the spinole; the inertias of the transmission parts; and the friction caused by the positioning wheels and lagers. The free run, without muscle stimulus, is performed to take these effects into account. Assumed is that, the free run and the actual experimental run follow the identical rotation pattern. In that case, the gravity, the inertia, and the friction forces are identical against time for both runs. Subtracting both motor signals against time leaves a motor current signal $i_{\text{res}}(t)$ that is only the result of the torque generated by the stimulated muscle fibres. Thus $i_{\text{res}}(t) = i_{\text{exp}}(t) - i_{\text{free}}(t)$ and $T_{\text{res}}(t) = i_{\text{res}}(t)rB_l$. The maximum generated torque of the muscle fibres is the maximum value of the torque signal during that experimental repetition.

The calculation of the generated work, $W(t)$ of an experimental repetition is based on the equation, $W(t) = \int T_{\text{res}}(t)\phi(t)\,dt$. Where $\phi(t)$ is the actual rotation signal and $T_{\text{res}}(t)$ is the resulting torque signal. Processing these signals, the work is calculated in a discrete equation.

$$W_j = \frac{1}{2} \sum_{i=0}^{j} T_i(\phi_{i+1} - \phi_{i-1}) \quad \forall \quad j \in [0, N] \quad (3.1)$$

3.2.5 Hardware

To realise the data acquisition of the dynamometer experiment, the same type of signal input hardware and signal processing software is used, as for the goal directed movement with collision experiment, see Section 2.2.3. One of the reasons to combine these experiments in one assignment and one of the main advantages of the Labview software is the fact, that the data acquisition of more experimental measurement setups can be realised, using the same data acquisition (DAQ) board and computer, by just changing the Labview program. Every program contains the specific processing routines for the matching experiment.

However, the fatiguing experiments are performed at the RUL in Maastricht. There, a Macintosh computer environment is used for data processing. Also a different National Instruments DAQ board is available. This DAQ board is identical with the LabPC+ board usable in an IBM
environment. The Labview software is compatible for both data acquisition hardware environments. Using other hardware, only a few default values in the software have to be adjusted. These values are adjusted in the data input.vi, see Section 2.2.4.

The LabPC+ board has 8 input/output channels. Its input resolution is 12 bit. The input voltage range is ±10.0 Volt. No pre acquisition filtering is available. The actual sample rate is based on a channel rate clock. The sample rate depends on the number of used channels.

3.2.6 Software

To perform the experiments two programs are written. First the rest length of the muscle has to be determined. Next the actual fatiguing test is performed. Like the software routines written for the goal directed movement with collision experiment, these routines are written in Labview, see Section 2.2.4.

Appendix D shows the front panel and the corresponding block diagram of both written software routines. As the definitive performance of the experiments is not clear yet, the software routines are still written in a raw form.

The program to determine the rest length, rustlengte bepalen.vi, processes the actual rotation signal and the control current signal into a data point. A series of these data points is used to create the muscle characteristic, torque against rotation curve. Besides the standard Labview routines three further routines are written.

The data inlezen.vi controls the functions of the DAQ board. This routine is identical to the data input.vi, used in the goal directed movement with collision experiment, see Section 2.2.4 except for some adjusted default values. The experiment are sampled during different periods of time with different sample rates.

The separate 4 channels.vi is also used in the movement experiment. It separates four data signals. In this case, the dynamometer has only three data channels.

The routine fitkromme.vi fits a fourth order polynomial through a set of data points and determines the maximum value and its corresponding rotation position.

The program vermoeiingsserieplus.vi is used to perform one bout of the fatiguing test. Here three signals, the actual rotation, the motor control current, and the muscle stimulus are measured per repetition. This program contains beside the standard and routines used in the rest length program, three further routines.

The arbeid.vi determines the generated work per repetition from the actual rotation and the resulting torque signal.

The routines save data/serie.vi and save data/herhaling.vi are routines save data, necessary for post processing. All values of the maximum torque and generated work per bout are saved. For every repetition, the resulting torque signal against time is of interest.
CHAPTER 3. RAT DYNAMOMETER

3.3 Model

3.3.1 Dynamometer

To model the dynamic behaviour of the dynamometer, the dynamometer is divided in four parts. The linear induction motor generates force depending on the control current as:

\[ F(t) = i(t)B \] (3.2)

The force equilibrium equation of the moving part of the motor:

\[ M_m \ddot{x} + b_m \dot{x} + k_m x = F(t) - F_{sp}(t) \] (3.3)

\( F_{sp} \) is the reaction force between the moving motor part and the spinole and \( M_m \) is the mass of the moving motor part. Motor properties cause the damping, \( b_m \) and the stiffness, \( k_m \). Round the windings an aluminium shell is placed. A movement of the shell generates an induction force. This causes the linear damping behaviour. The internal stiffness component is negligible in the dynamic behaviour of the moving part of the motor.

The spinole is a rigid body, that conducts the translation, \( x(t) \) generated by the motor. The spinole and the moving part of the motor move in the gravity field. This causes continuous gravity force, \( F_g \). The positioning wheels are connected with the solid world with bearings. These bearings, angular contact bearings, cause constant Coulomb friction force, \( F_c \) opposed to the movement direction. The friction of these bearings depends on their friction constant \( f_c \). A spring pushes the wheels on the spinole. This spring causes a constant normal force on the bearings. With a friction constant independent of the rotation velocity, the friction torque generated by the bearing is constant and opposed to the movement direction. Accept if the bearings are not moving, then the friction constant is unknown. The friction force, \( F_w \) applied on the spinole of the four wheels assembled:

\[ F_w(t) = -\text{sign}(\dot{x}(t))F_c \quad \forall \quad \dot{x} \neq 0 \\
- F_c \leq F_w(t) \leq F_c \quad \forall \quad \dot{x} = 0 \] (3.4)

The force equilibrium equation of the spinole:

\[ M_{sp} \ddot{x} = F_{sp}(t) - F_g - F_w(t) - F_{tr}(t) \] (3.5)

\( M_{sp} \) is the mass of the spinole and \( F_{tr} \) is the reaction force between spinole and transmission.

The third part is the transmission wheel. The transmission functions without skid. The transmission relations:

\[ x(t) = r \phi(t) \] (3.6)

\[ T_{ro}(t) = r F_{tr}(t) \]

The transmission ratio, \( r \) is the rotation wheel radius. \( T_{ro} \) is the reaction torque between the transmission and the rotation axis.

The rotation axis provides the rotation for the ankle joint. In reality there is a further part, the rat foot holder, between the rotation axis and the rat ankle. The influence of this part is not considered here. The bearings also position the rotation axis. The here caused friction is already included in the friction, \( F_w \) of the spinole. The rotation axis torque equilibrium equation:

\[ J_{ro} \ddot{\phi}(t) = T_{ro}(t) + T_{rat} \] (3.7)
3.3. MODEL

$J_{ro}$ is the inertia of the rotation axis. The torque generated by the rat, $T_{rat}$ is built up of: non-stimulated muscle force and rat inertias; and stimulated muscle force.

The rat foot holder causes natural eigenfrequencies in a range of $f > 800\,Hz$. Because of the strong damping properties in the motor, the dynamometer operates only in a lower frequency range $f < 100\,Hz$.

The total dynamic model is built up from the four parts, see Figure 3.6. From now on the internal motor stiffness, $k_m$, the inertias of the bearings are neglected. The stiffnesses of the spinole, $k_{spinole}$, and the rotation axis $c_{rot.axis}$ are considered to be infinite stiff. The natural eigenfrequencies of these parts lie far outside the operation range of the motor. Using these assumptions, the dynamic model is simplified to a one degree of freedom model, see Figure 3.7.

![Figure 3.6: The dynamic model of the dynamometer, the properties of the motor, the spinole, the transmission, and the rotation axis are compiled.](image)

![Figure 3.7: The simplified dynamic model of dynamometer. Linearisations and simplifications leave a one degree of freedom model.](image)

The dynamic behaviour of this simplified model:

$$\frac{1}{r}J_{tot}\ddot{\varphi} + rb_m\dot{\varphi} = F(t) - F_w(t) - F_z + \frac{1}{r}T_{rat}$$

All moving inertias of the system are added in the total inertia, $J_{tot} = r^2(M_m + M_{sp}) + J_{ro}$.

3.3.2 Control system

A PID controller controls the dynamic behaviour of the dynamometer. The controller generates the motor current. In the controller, the actual rotation signal is compared with the set-point signal. The differentiating D action is only inflicted on the feedback, the actual rotation signal. The proportional and integrating action are inflicted on the difference between set-point signal and feedback signal. The PID controller is built up from electronical components: the resistors $R_i$; the capacitors $C_i$; and an operational amplifier (opamp), see Figure 3.8.
CHAPTER 3. RAT DYNAMOMETER

Figure 3.8: The PID controller. The set-point and the feedback signals are compared in the controller. The electronic components transfer both input voltages into the output voltage $V_u$. The output signal is transferred into the motor control current.

The opamp is considered to be ideal, to have no current leak. This means $V^+ = V^- = 0$. In this case the relation between the output voltage, $V_u$ and the two input signals can be described in the Laplace domain, see Beek [3]:

$$-V_u(s) = \left(R_2 + \frac{1}{C_2 s}\right)\left(\frac{1}{R_1}V_{\text{setpoint}}(s) + \left(\frac{1}{R_1} + \frac{1}{R_3 + \frac{1}{C_1 s}}\right)V_{\text{feedback}}(s)\right)$$  \hspace{1cm} (3.9)

Physically the two input signal currents are added in the controller. To obtain a difference signal in the controller the feedback voltage is inverted before it is offered to the controller. The outgoing voltage is amplified before it is processed in to obtain the motor control current. In this amplifier, the outgoing voltage is also inverted. Without this further inversion the actual rotation signal would be mirrored to the set-point signal.

3.3.3 Total transfer function

With knowledge of the transfer functions between input and output signals of the dynamometer, the responses can be simulated. Comparing simulations to actual experimental measurement values of internal properties and assumptions can be verified. The system has two input and two output signals. The inputs of the system are the set-point signal and the externally generated force, $E_f$. Beside the torque generated by the rat also the friction and gravity forces are included in the external force, $E_f(t) = \frac{1}{2}T_{\text{rat}}(t) - F_w(t) - F_z$. The rat torque is the value, that has to be determined. The friction however is a non-linear factor in this model. When the actual rotation speed is zero, its value is unknown. Else its value depends on the direction of the rotation speed.

Figure 3.9 shows the whole system in a closed loop block diagram. $H_i(s)$ are the partial transfer functions representing the control behaviour and the dynamic behaviour of the dynamometer. $K_i$ are linear constants. $K_1,2,4$ are electronic resistors. They transfer currents into voltages or the other way around. $K_3$ describes the motor behaviour. $K_5$ models the behaviour of the potentiometer. The actual rotation causes a corresponding voltage.
Figure 3.9: Block diagram of the total dynamical closed loop system of the dynamometer. The set-point signal and the external forces are the inputs of the system, the measured torque and actual rotation signals are the two outputs.

The relation between inputs and outputs:

\[ R(s) = H_{13}(s)S_p(s) + H_{14}(s)E_f(s) \]  
\[ T(s) = H_{23}(s)S_p(s) + H_{24}(s)E_f(s) \]  

(3.10)  

The circumferential transfer function:

\[ \hat{H}(s) = -H_1(s)K_2K_3H_3(s)K_5H_2(s) \]  

(3.11)  

The direct transfer functions between input and output signals:

\[ H_{d13}(s) = K_1H_1(s)K_2K_3H_3(s)K_5 \]  
\[ H_{d14}(s) = H_3(s)K_5 \]  
\[ H_{d23}(s) = K_1H_1(s)K_2K_4 \]  
\[ H_{d24}(s) = -H_3(s)K_5H_2(s)H_1(s)K_2K_4 \]  

(3.12)  
(3.13)  
(3.14)  
(3.15)  

The total transfer functions between input and output signals:

\[ H_{ij}(s) = \frac{H_{dij}(s)}{1 - \hat{H}(s)} \]  

(3.16)  

The actual values of the partial transfer functions and linear constants are given in Appendix C.
CHAPTER 3. RAT DYNAMOMETER

3.4 Conclusions & Recommendations

3.4.1 Conclusions

The generated work and maximum torque are the parameters, that quantify the muscle performance during a repetition. During the period where there is no change in the actual rotation, $\phi = \text{const}$, an unknown input in the external force, the friction influences the measured responses. The resulting torque signal is only valid for the period where the actual rotation is started. The maximum generated torque value is the maximum value of this signal. The resulting torque is the result of the muscle stimulus. This stimulus starts prior to the start of the actual movement. In general muscle fibres fatigue in time and as result of that the muscle performance decreases. Thus the optimum of the generated torque would lie in the movement less period that is influenced by the non-linear friction behaviour. However, depending on the muscle elongation velocity and the elongation direction during the actual movement, the muscle force is extra increased. In this case the generated torque during the movement period could exceed that of the movement less period. Under these movement conditions, these specific muscle properties provide the maximum generated torque to lie within the operating range of the dynamometer. In general this will not be the case, the generated torque optimum will lie in the inaccurate range.

The generated work is determined from the actual rotation and the resulting torque signal, $W = \int T_{\text{res}} \phi$. During the period where the resulting torque signal is not valid, the actual rotation signal is constant. This means that the $\phi$ term is zero. Thus no work is generated during this period. If the described model is accurate, the calculated work value is valid. However muscle stimulus costs generation of energy in the muscle. In the movement less period, this energy is produced in another form as work.

3.4.2 Recommendations

To quantify the results of the experiments properly, the results of the output signals have to be gauged. There are three main relations between the actual measurements and the properties they have to describe: the relation between rotation signal, $R(t)$ and the actual rotation, $\phi(t)$; the relation between the motor control current, $i(t)$ and the actual external force, $E_f(t)$; and the relation between the residual motor current, $i_{\text{res}}$ and the actual torque generated by the rat, $T_{\text{rat}}$. These relations are described with linear equations. The operation range of these relations has to be determined, and the used values for the model constants have to be verified. The actual influence of the non-linear friction behaviour is requires attention.

Beek [3] has already performed several gauging experiments. With the use of the artificial rat foot external torque patterns can be generated.

In the current measurement setup it is recommendable to measure only signals within the operating range of the dynamometer, thus during the movement period. The results of these measurements do not provide the optimum values of the muscle performance, but these results are comparable.
3.5 Nomenclature

The following signs and abbreviations are used in this chapter "Rat dynamometer".

**Roman characters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_m$</td>
<td>Damping constant; motor property</td>
<td>kg/s</td>
</tr>
<tr>
<td>$c_{rot.axis}$</td>
<td>Rotational stiffness of the rotation axis</td>
<td>Nm</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency range</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Coulomb friction constant</td>
<td>A</td>
</tr>
<tr>
<td>$i(t)$</td>
<td>Motor control current</td>
<td>A</td>
</tr>
<tr>
<td>$i_{exp}(t)$</td>
<td>Control current during an experimental run</td>
<td>A</td>
</tr>
<tr>
<td>$i_{free}(t)$</td>
<td>Control current during the free run</td>
<td>A</td>
</tr>
<tr>
<td>$i_{rea}(t)$</td>
<td>Resulting control current</td>
<td>A</td>
</tr>
<tr>
<td>$k_m$</td>
<td>Stiffness constant; motor property</td>
<td>N/m</td>
</tr>
<tr>
<td>$k_{spinole}$</td>
<td>Stiffness of the spinole, elasticity</td>
<td>N/m</td>
</tr>
<tr>
<td>$r$</td>
<td>Transmission constant, radius of the transmission wheel</td>
<td>m</td>
</tr>
<tr>
<td>$r^*$</td>
<td>Ratio transmitting rotation angles from radians into degrees</td>
<td>rad$^{-1}$</td>
</tr>
<tr>
<td>$t$</td>
<td>Time base</td>
<td>s</td>
</tr>
<tr>
<td>$t_s$</td>
<td>Start point of the rotation</td>
<td>s</td>
</tr>
<tr>
<td>$x(t)$</td>
<td>Translation of the motor</td>
<td>m</td>
</tr>
<tr>
<td>$B_l$</td>
<td>Motor constant, Magnetic flux times the actual range of the winding area</td>
<td>N/A</td>
</tr>
<tr>
<td>$C_i$</td>
<td>Capacitor values</td>
<td>F</td>
</tr>
<tr>
<td>$E_f(t)$</td>
<td>Externally generated force</td>
<td>N</td>
</tr>
<tr>
<td>$F(t)$</td>
<td>Motor force</td>
<td>N</td>
</tr>
<tr>
<td>$F_c$</td>
<td>Coulomb friction</td>
<td>N</td>
</tr>
<tr>
<td>$F_{sp}$</td>
<td>Reaction force between motor and spinole</td>
<td>N</td>
</tr>
<tr>
<td>$F_{tr}$</td>
<td>Reaction force between spinole and transmission</td>
<td>N</td>
</tr>
<tr>
<td>$F_w$</td>
<td>Friction</td>
<td>N</td>
</tr>
<tr>
<td>$F_g$</td>
<td>Gravity</td>
<td>N</td>
</tr>
<tr>
<td>$H_i(s)$</td>
<td>Transfer functions</td>
<td>varies</td>
</tr>
<tr>
<td>$J_{ro}$</td>
<td>Inertia of the rotation axis</td>
<td>kgm$^2$</td>
</tr>
<tr>
<td>$J_{tot}$</td>
<td>Inertia of the whole system</td>
<td>kgm$^2$</td>
</tr>
<tr>
<td>$K_i$</td>
<td>System constants</td>
<td>varies</td>
</tr>
<tr>
<td>$M_m$</td>
<td>Mass of the moving part of the motor</td>
<td>kg</td>
</tr>
<tr>
<td>$M_{sp}$</td>
<td>Mass of the spinole</td>
<td>kg</td>
</tr>
<tr>
<td>$R(t)$</td>
<td>Rotation signal</td>
<td>V</td>
</tr>
<tr>
<td>$R_i$</td>
<td>Resistor values</td>
<td>Ω</td>
</tr>
<tr>
<td>$T(t)$</td>
<td>Rotation axis torque</td>
<td>Nm</td>
</tr>
<tr>
<td>$T_{rat}(t)$</td>
<td>Torque generated by the rat</td>
<td>Nm</td>
</tr>
<tr>
<td>$T_{rea}(t)$</td>
<td>Resulting rotation axis torque</td>
<td>Nm</td>
</tr>
<tr>
<td>$T_{ro}$</td>
<td>Reaction torque between transmission and rotation axis</td>
<td>Nm</td>
</tr>
<tr>
<td>$V^-$</td>
<td>Inverting voltage input of the operational amplifier</td>
<td>V</td>
</tr>
<tr>
<td>$V^+$</td>
<td>Positive voltage input of the operational amplifier</td>
<td>V</td>
</tr>
<tr>
<td>$V_u$</td>
<td>Output voltage of the controller</td>
<td>V</td>
</tr>
<tr>
<td>$W(t)$</td>
<td>Generated work</td>
<td>J</td>
</tr>
</tbody>
</table>
Greek characters

\( \alpha \)  
Angle in the rotation pattern, rotation velocity  \( \text{rad/s} \)

\( \phi(t) \)  
Rotation of the rotation axis  \( \text{rad} \)

\( \phi_{\text{max}} \)  
Maximum deflection of the rotation pattern  \( \text{rad} \)

\( \phi_{\text{min}} \)  
Minimum deflection of the rotation pattern  \( \text{rad} \)
Chapter 4

Conclusions

In this research the data acquisition of two experimental measurement setups is combined. The conclusions and recommendations specific for the two independent experiments are noted in the Sections 2.5 and 3.4 of the corresponding chapters.

Both experiments are set up to describe kinesiological phenomena with technological properties. For this purpose, experimental setups are designed and built, in such manner that under certain experimental conditions, certain measurements can be performed. The development of these apparatus, shows that it requires good communication between both scientific environments. This in order to realise an experimental measurement setup, that is used and useable in its practical and desired operating range, and that provides the accurate technological properties to support the correct kinesiological theories.
Bibliography


Appendix A

Sample rate influences

To determine the required sample rate, the influence of the sample rate on the maximum force and the impulse level is investigated. Therefore a drop test is performed and the force signal is measured. This original signal is sampled with $f_{sam} = 32kHz$ and filtered with $f_{fil} = 16kHz$. From this signal the maximum force and impulse level are determined. Next this signal is post processed, simulating sampling of the same experiment with a smaller sample rate. This procedure is performed three times. First filtered with $f_{fil} = 8kHz$ and sampled with $f_{sam} = 16kHz$. Second filtered with $f_{fil} = 4kHz$ and sampled with $f_{sam} = 8kHz$. And third filtered with $f_{fil} = 2kHz$ and sampled with $f_{sam} = 4kHz$. For all these signals the maximum force and the impulse step is determined.

This research is performed for both pens, the original pen and the modified pen. The four signals are shown together in one plot. Figure A.1 shows the force signals for the original pen and Figure A.2 shows the force signals for the damped pen.

![Figure A.1: The influence of the sample frequency on the force peak, using the original pen. A measured signal (32 kHz) and three processed (16, 8, and 4 kHz) signals, as a result of a drop test, are shown.](image1)

![Figure A.2: The influence of the sample frequency on the force peak, using the damped pen. A measured signal (32 kHz) and three processed (16, 8, and 4 kHz) signals, as a result of a drop test, are shown.](image2)
The maximum values of the force signals are quantified in Table A.1.

<table>
<thead>
<tr>
<th>Pen</th>
<th>$F_{\text{max}}$ [N]</th>
<th>Pen</th>
<th>$F_{\text{max}}$ [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$32, kHZ$</td>
<td>308</td>
<td>$32, kHZ$</td>
<td>135</td>
</tr>
<tr>
<td>$16, kHZ$</td>
<td>319</td>
<td>$16, kHZ$</td>
<td>134</td>
</tr>
<tr>
<td>$8, kHZ$</td>
<td>230</td>
<td>$8, kHZ$</td>
<td>126</td>
</tr>
<tr>
<td>$4, kHZ$</td>
<td>181</td>
<td>$4, kHZ$</td>
<td>117</td>
</tr>
</tbody>
</table>

All force signals are integrated. The result, the impulse signals are shown in Figure A.3, for the original pen, and A.4, for the damped pen.

**Figure A.3:** The influence of the sample frequency on the impulse signal, using the original pen. A measured signal ($32\, kHZ$) and three processed ($16$, $8$, and $4\, kHZ$) signals, as a result of a drop test, are shown.

**Figure A.4:** The influence of the sample frequency on the impulse signal, using the damped pen. A measured signal ($32\, kHZ$) and three processed ($16$, $8$, and $4\, kHZ$) signals, as a result of a drop test, are shown.
Appendix B

Specification of the transition points in the time reference signal

The behaviour of the time reference signal round the transition points is investigated. The time reference signal is measured for a two step, large target experiment, and for a two step, small target experiment. The signals are sampled with $f_{sam} = 8kHz$. The total time reference signal of the large target experiment is shown in Figure B.1. The transitions round the four time points $T_0 - T_3$ are shown in the Figures B.2 - B.5.

![Figure B.1: The time reference signal of a two step, large targets experiment. The dashed lines show the four time points ($T_0 - T_3$).](image)
APPENDIX B. SPECIFICATION OF THE TRANSITION POINTS IN THE TIME REFERENCE SIGN.

Figure B.2: The transition of the time reference signal at the start of the movement from the start point. The dashed line shows the time point $T_0$.

Figure B.3: The transition of the time reference signal at the landing on target point one. The dashed line shows the time point $T_1$.

Figure B.4: The transition of the time reference signal at the start from target point one. The dashed line shows the time point $T_2$.

Figure B.5: The transition of the time reference signal at the landing on target point two. The dashed line shows the time point $T_3$. 
Figure B.6 shows the time reference signal of the two step small target experiment. The transitions round the four time points \( T_0 - T_3 \) are shown in the Figures B.7 - B.10.

Figure B.6: The time reference signal of a two step, small targets experiment. The dashed lines show the four time points \( (T_0 - T_3) \).
Figure B.7: The transition of the time reference signal at the start of the movement from the start point. The dashed line shows the time point $T_0$.

Figure B.8: The transition of the time reference signal at the landing on target point one. The dashed line shows the time point $T_1$.

Figure B.9: The transition of the time reference signal at the start from target point one. The dashed line shows the time point $T_2$.

Figure B.10: The transition of the time reference signal at the landing on target point two. The dashed line shows the time point $T_3$. 
Appendix C

Dynamometer model constants

Linear constants:

\[
\begin{align*}
K_1 &= \frac{1}{R_1} = 1.10 \times 10^{-5} \Omega^{-1} \quad \text{: resistor} \\
K_2 &= \text{Amp.}\frac{1}{R_3} = 2 \Omega^{-1} \quad \text{: resistor & amplifier} \\
K_3 &= Bl = 12 N/A \quad \text{: motor constant} \\
K_4 &= R_5 = 5 \Omega \quad \text{: resistor} \\
K_5 &= Pot.r^* = 0.1 V/rad \quad \text{: potentiometer}
\end{align*}
\]

Linear transfer functions:

\[
\begin{align*}
H_1(s) &= + \left( R_2 + \frac{1}{C_2 s} \right) \\
H_2(s) &= \frac{1}{R_1} + \frac{1}{R_3 + \frac{1}{C_1 s}} \\
H_3(s) &= \frac{r}{J_{tot} s^2 + b_m r^2 s}
\end{align*}
\]

With:

\[
\begin{align*}
R_1 &= 1.10^5 \Omega \\
R_2 &= 1.10^6 \Omega \\
R_3 &= \frac{1}{3} \times 10^5 \Omega \\
C_1 &= 88.10^{-9} F \\
C_2 &= 22.10^{-9} F \\
r &= 15.10^{-3} m \\
J_{tot} &= 1.04.10^{-6} kgm^2 \\
b_m &= 0.05 kg/s \\
r^* &= 57.3 rad^{-1}
\end{align*}
\]

The extra transmission ratio \( r^* \) is used, because the set-point and the feedback signal represent the rotation in degrees instead of in radians.
Appendix D

Labview software, virtual instruments

*Target.vi* is the main program to perform the goal directed movement experiment with collision. The results of the experiments performed by van Loon [2] are obtained with this program. Figure D.1 shows the hierarchical structure of the program. The main program uses several sub VIs. Most of these sub VIs are basic Labview routines. Several new routines have been written. The front panels and the block diagrams of the main program and the new sub VIs are shown in Figures D.2 - D.8.

The VIs *rustlengte bepaling.vi* and *vermoeiingsserie.vi* are the main programs to perform the fatiguing experiment. The determined rest length (*rustlengte bepaling.vi*) is used in the actual fatiguing experiment *vermoeiingsserie.vi*. Figures D.9 & D.10 show the hierarchical structure of both programs. The main programs and the new sub VIs are shown in Figures D.3, D.5, D.12 - D.16.
Figure D.1: The hierarchical structure of the main program target.vi and its subVIs. Only the new subVIs are specified.
Figure D.2: The front panel and the block diagram of the main program, `target.vi`. The front panel shows the results of the experimental run. The block diagram, the actual software processes the data currents.
Figure D.3: The front panel and the block diagram of the subVI, *data input.vi*. Here the data acquisition board actions are specified.
Figure D.4: The front panel and the block diagram of the subVI, `timepoints.vi`. The VI determines the time transition points from the time reference signal.
Appendix D. Labview Software, Virtual Instruments

Figure D.5: The front panel and the block diagram of the subVI, separate 4 channels.vi. The two dimensional data array is separated in four data rows.

Figure D.6: The front panel and the block diagram of the subVI, thresholdlevel.vi. The VI determines the point, where the time reference signal crosses the specified threshold level.
Figure D.7: The front panel and the block diagram of the subVI, mean signal part.vi. The mean value of a data array is determined.
Figure D.8: The front panel and the block diagram of the subVI, integrator.vi. This VI is a numerical integration routine, that provides the integration pattern of the input array.
Figure D.9: The hierarchical structure of the main program, rustlengte bepaling.vi. The optimum rest length of the fatigued muscle is determined.
Figure D.10: The hierarchical structure of the main program, *vermoeiingsserie.vi*. This is the program to perform the actual fatiguing experiment.
Figure D.11: The main program, *rustlengte bepaling.vi*. The front panel shows a graph with the measured data points and the fit fourth order polynomial. The program determines the optimum value of the fit function.
Figure D.12: The fitkromme.vi fits a fourth order polynomial through a set data points.
Figure D.13: The main program `vermoeingsserie.vi` determines the generated torque and work values for one bout of experimental runs.
Figure D.14: The arbeid.vi is a numerical routine, that calculates the generated labour from the actual rotation and the resulting torque signals.
Figure D.15: The save data/herhaling routine specifies the information to save what data per experimental run.

Figure D.16: The save data/serie routine specifies the information to save what data per experimental bout.