Developing a wearable system to assess balance during advanced dynamic movements

- A pilot study -

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Abstract - Current rehabilitation methods for stroke and spinal cord injury patients are inadequate in preparing patients for independent daily life. Additionally assessment methods are susceptible to errors as patients are qualitatively evaluated. The effect of this is observed in the fact that up to 39% of stroke patients and 45% of spinal cord injury patients experience falls post rehabilitation.Studies have suggested that alternative training methods, involving advanced dynamic movements such as Tai Chi and Pilates, could be an improvement to currently used methods. This study propose to develop a wearable system with a combination of force sensitive resistors and gyroscopes to evaluate on balance performance during advanced dynamic movements, such as karate, to test if it is possible to quantify performance and balance at different experience levels of karate. ***Method*** Three subject were included, with varying experience at karate. Force sensitive resistors were placed under the soles to measure pressure distribution during a specific karate sequence. Gyroscopes were placed at the knees to measure angular velocities. Data were filtered with a third order low pass Butterworth filter, cutoff at 2.5Hz for pressure data, cutoff at 1.25Hz for gyroscope data. A performance score was calculated, based on four measures. Depending on data-distribution, a one-way ANOVA or Kruskal-Wallis statistical test was used. Bonferroni correction was applied to correct for false results. ***Results*** No significant differences were found between measures. A significant difference in performance score was found between the novice and master subjects ($p < 0.05$).
Conclusion The study concludes that balance is improved with experience in karate. However, the authors recommend that further studies should be conducted in the research area in order to determine the possibility of quantifying advanced dynamic movements with wearable systems.

Contents

1 | Introduction

A major struggle for people recovering after stroke and spinal cord injury (SCI) is regaining the ability to walk. This is one of the main focus points of the rehabilitation, as walking is one of the key factors to living a normal, independent life. However, the currently used rehabilitation methods are not enough to properly train patients' balance and walking ability, as patients remain at a high risk of falling even after the rehabilitation period [1, 2, 3, 4, 5].

A plausible reason for this is that current rehabilitation methods and evaluations are not properly preparing patients for independent daily life. Current rehabilitation methods include gait training on treadmills. Herein lies a problem, as it has been shown that training in clinical environments translate poorly to real life [6]. Additionally current methods for assessing patients in stroke and SCI rehabilitation are based on qualitative psychometrics which can be difficult to make standardised outcome measures on [7, 8, 9, 10].

Thus it is relevant to investigate new training methods for rehabilitation of stroke and SCI patients. Few studies have investigated the effects of training using non standard methods. A 2017 systematic review and meta-analysis study by Moreno-Segura et al. [11] found that Pilates training improved balance in older adults resulting in fewer falls.Winser et al. [12] also conducted a systematic review and meta-analysis, investigating changes in balance performance of stroke and Parkinson's disease patients following Tai Chi training. Winser et al. could conclude that Tai Chi training is effective in reducing falls when compared to no training.

Research suggests that advanced dynamic movement training is an alternative to and possible could be an improvement to current training methods. To further investigate this research area, this study proposed to examine the effect of training with karate as a form of advanced dynamic movements for improving balance. To investigate this a wearable and lightweight system, which does not prevent movements during karate performance, should be used. However, current training methods for rehabilitation are not able to do measures of advanced dynamic movements. It is therefore necessary to develop a system capable of measuring the balance during advanced dynamic movements performed in karate.

2 | Problem Analysis

2.1 Cardiovascular Diseases

Cardiovascular diseases (CVD) are the number one cause of death on a world wide scale. In 2015 CVDs was estimated to account for more than 31% of all deaths globally [13]. CVD are a collected term for a number of conditions revolving around diseases to the heart and system of blood vessels. According to the World Health Organisation (WHO) the top two causes of global deaths are the CVDs coronary artery disease and stroke. Of the two, stroke accounted for 10% of deaths in 2016 [14].

2.1.1 Stroke

A stroke is caused by either a blockage or rupture of blood vessels in the brain. As such stroke is divided into two subtypes; ischaemic stroke and haemorrhagic stroke. During an ischaemic stroke a blood vessel in the brain is blocked by blood clots caught in narrow blood vessels. The narrowing of blood vessels are commonly caused by other conditions such as high cholesterol, high blood pressure, unhealthy lifestyle and ageing. If a blood vessel is blocked a part of the brain will be shut off from its blood supply. If not treated within minutes this can cause damage to brain cells in the cut-off area [15, 16, 17]. During an haemorrhagic stroke a blood vessel will rupture and blood will leak inside the brain. Depending on where in the brain the leak occurs the haemorrhagic stroke is either a intracerebral haemorrhage or and subarachnoid haemorrhage, intracerebral being inside the brain and subarachnoid occurring in the space between the brain and the cranium. In both types a rupture and leakage of blood can cause a sudden increase in pressure potentially causing damage to brain cells and can lead to sudden unconsciousness and death. The most common causes are high blood pressure, unhealthy lifestyle, diabetes and ageing [15, 18, 17].

2.1.2 Stroke Complications

Complications following a stroke are common. In surviving patients 30-96% have been reported to experience post-stroke complications of both physical and psychological nature. Complications involve recurrent stroke and epileptic seizures, cardiac arrhythmias and failure, infections, problems in gastrointestinal and genitourinary systems, complication of immobility, dementia, pain and depression [5]. Thus, the consequences are many, however this study will focus on complications of mobility. Following a stroke complications related to movement are common. Depending on where in the brain the stroke occurs it can have a variety of outcomes that can affect the patients balance and motor control [19]. Up to 38% of stroke patients have been reported to experience spasticity affecting the performance of dynamic muscle movements such as gait. Spasticity and motor control changes can occur following an upper motor neuron lesion.Stroke patients are also at a higher risk of osteoporosis due to weakening of performing voluntary movements or movements as a whole if the patient experience hemiparesis [5, 19].

2.2 Spinal Cord Injury

The spinal cord (SC) is part of the central nervous system (CNS) together with the brain. The SC is connecting the brain to the rest of the body by the peripheral nervous system (PNS). It is responsible for leading nerve impulses between the brain and body, to modulate movements, sensory inputs and visceral innervation. The SC extends from the brain just below the cranium down the spine to the lumbar vertebrae one and two (L1-L2). From L1-L2 to the cauda equina at the coccyx vertebrae or tail bone, bundles of nerve fibres extend further. The vertebrae bones encapsulates and protects the SC. However, trauma to the spine can cause trauma to the SC as well [20].

The incidence for spinal cord injuries (SCI) ranges from 15 to 39 million a year in industrialized countries. Most traumatic causes are a result of traffic accidents, falls and violence. Causes for non-traumatic SCI are degenerative diseases and tumours. In prevalence of traumatic SCI, men outnumber women at a ratio of 3:1, while the prevalence is near equal in non-traumatic SCI. According to the National Spinal Cord Injury Statistical Center (NSCISC), the most frequent category for neurological damage is incomplete quadriplegia at 32.2% of cases. This is followed by complete paraplegia at 24.2%. Out of all SCI cases only 7.4% reach neurological recovery [21].

2.2.1 Complications of SCI

Any injury to the SC causing neurological damage can lead to serious dysfunction depending on where the injury happens. This can lead to loss of sensory sensation and motor control and dysfunction to bladder, bowel and cardiovascular functions [20, 19]. As mentioned earlier, this project will focus on complications of mobility. Many SCI patients experience rehospitalization, depression and pain, following the injury. According to the NSCISC many patients are unsatisfied with their life in the years after injury. However, life satisfaction generally increases with years post injury [21].

2.3 Rehabilitation

Patients suffering from neural damage caused by stroke or SCI will in many cases need to go through a rehabilitation process to regain or relearn lost functions [22, 23]. Currently many different methods for rehabilitation exist, many with focus on patients regaining control of limbs. Many patients suffer from loss of the ability to walk properly, as a result of losing control of the lower limbs. A giant step toward regaining autonomy and independence in daily life is to train patients balance and ability to walk again.

Rehabilitation programs for both stroke and SCI patients often involves training gait and the sensory-motor (SM) system in the brain. Studies have shown that due to neural plasticity patients can regain lost functions with training [24, 22, 25]. Rehabilitation training functions through repetition of specific gait tasks while utilizing feedback to achieve improvements in gait coordination, speed and strength [24]. The training is often conducted using treadmills, on which the patient will attempt to walk while being supported by an unloading harness. This training method can consist of both explicit and implicit methods; the explicit method is where patients will receive visual feedback to adjust the length of their steps in order to activate a cognitive process to adjust their gait. The implicit method will rely on resistance in order to train locomotion without the patient having to plan their step length. Another important aspect of rehabilitation of these individuals is their balance, and lately training of this ability has been shown to increase both speed and distance in walking tests [22].

An important aspect of rehabilitation is that when assigning training to participants of stroke or SCI, it is important to evaluate the state of the participant, as different participants will have different levels of dysfunction depending on the severity of the damage caused by stroke or SCI. Rehabilitation should be suited to each participant individually [22, 19].

2.4 Assessing Gait in Rehabilitation

During rehabilitation patients must be assessed to evaluate the progressing of the rehabilitation process. Several different methods for assessing patient gait abilities have been developed to evaluate on the rehabilitation progress.

2.4.1 Measuring Gait in a Clinical Environment

Recent technological improvements makes it possible to perform advanced gait analysis (GA) while examining 3D kinematics and EMG in a clinical setting. This method provides the clinician with an advanced insight in the patients current abilities and gives the possibility of measuring and quantizing any changes that might occur during a rehabilitation process [22].

The method of using 3D kinematics takes place in a laboratory with the use of cameras, surface electromyography (sEMG), force platforms and stereophotogrammetry equipment to provide the needed data to perform GA. The system provides recordings for qualitative analysis, as well as quantitative measures of muscle activation, contact forces with the ground and body position during gait. These measures are used to evaluate the gait cycle with regards to step length, cadence, swing time, rotation and power in the joints for the individual subject [22].
An attempt to quantify the quality of gait with a single parameter is the Normalcy Index (NI). This algorithm measures deviation of a patients gait pattern from the gait of healthy individuals through Principal Component Analysis (PCA). The mean pattern is based on some of the features obtained with GA. This method has been proven to be an effective tool to examine changes in gait over time [22]. Further advances in the quantification of the many features is the gait deviation index, the gait profile score and the movement deviation profile. All of these methods take different approaches to finding the deviation between healthy gait and the measured variables from the advanced clinical set-up described briefly above [22].
Other approaches exist to measure improvement during rehabilitation. One study calculated the combined centre of pressure of the patient and a walking frame (WF) as a combined system, by measuring reaction forces of both the patient and the WF along with cameras capturing

the placement of the feet relative to the WF. This gave the possibility to calculate the weight supported through the frame and the stability of both patient and WF [26].

2.4.2 Measuring Gait outside a Clinical Environment

Methods of measuring gait and other dynamic activities outside clinical environments are becoming more accessible and favourable over measurement methods bound to clinical environments. Rehabilitation and assessment in clinical environments rarely translate well to real life situations [6]. Such systems are most functional if they are wearable by the patient or test subject.

Wearable systems to analyse and monitor body dynamics are attracting an increased interest in research, where inertial measurement units (IMU) are the most used in recent studies. Here, studies have used wearable systems to measure upper limb kinematics and trunk posture, to evaluate on movement performance [27]. Wearable systems can also be used for assessing gait by implementing multiple sensors placed on the subjects lower limbs, measuring variables such as acceleration, gyroscopic, pressure forces and EMG depending on which system is implemented. Here, measuring forces applied to the feet can be done with force sensors based on either resistive, piezoelectric or capacitive designs, and often includes an implementation of these in shoes or insoles [28]. A study by Muro et al. [28] has been shown that the implementation into insoles reflects the measurements obtained from clinical motion analysis laboratories. Inertial measurement units (IMU) can also be implemented in wearable devices. These consist of gyroscopes measuring the rotational inertia used to measure changes in direction, as well as accelerometers measuring the acceleration in three axes giving the opportunity to measure changes in balance or sudden shocks such as those experienced by the sensor while walking [28].

A study by Hurwitz et al. [29], examined the importance of accelerometer position, age and walking speed on the accuracy of accelerometer based measurement of gait. It was found that the device location did not affect measures such as speed, cadence and single limb support time. Gait asymmetry and variability was shown to be affected by age and walking speed.

2.4.3 Shortcomings of Current Rehabilitation

It is known that clinical trials and training translates poorly to daily life outside clinical environments, however still current rehabilitation mainly perform training in clinical environments, or train tasks which poorly portrait normal daily life [6]. This is a problem since both stroke and SCI patients experience a greater risk of falls. The prevention of patients falling should be prioritized in rehabilitation as falls can lead to loss of independence and serious injury [19]. Despite the consequences, studies have shown that 30-39% of stroke patients fall at least once during a rehabilitative process, and of these patients 42% experience multiple falls [5, 2]. According to a study by Wannapakhe et. al [3], out of a group of 100 SCI patients, 45 experienced falls during a six month period post rehabilitation. Apart from the immediate risks and dangers to patients falling, falls can also further extend the rehabilitation period and worsen the rehabilitation of both motor and cognitive functions [4, 1]. This is a problem since strength recovery is usually greatest in the first 100 days following injury [20], but continues to improve even years after the stroke incident [30]. An additional risk for both stroke and SCI patients is cardiovascular events during training, due to a decreased functional capacity following the incidents [19].

In addition, current rehabilitation programs still use qualitative methods for evaluating patients progress. These methods rely on the physician to evaluate how well the patient performs [8, 9, 10]. This is a problem since qualitative evaluations are based on psychometrics which are prone to changes between sessions depending on many factors which are difficult to account for, like the patients level of energy or the physicians personal experience. This could be a problem since patients are observed to experience falls post rehabilitation [5, 2, 3]. This might suggest that current evaluation methods does not properly evaluate whether or not patients are fit for independent daily life.

2.4.4 New Methods for Balance and Gait Training

In contrast to current rehabilitation methods, mainly focusing on simple gait training, a rhythmic movement, newer approaches have begun to use dual-task training, incorporating cognitive tasks as well. Studies have also been investigating the use of withdrawal reflexes to rehabilitate walking in hemiparetic and stroke patients [31, 32]. Training involving advanced movements have suggested to improve balance for both stroke and Parkinson's disease patients [33, 12].

Studies have shown that dual-task mobility training helps improve balance and gait compared to groups that performed single-task training in stroke patients. The dual-task approach was designed to make the patient walk on a treadmill while performing either a cognitive or motor task at the same time [34]. The walking/motor dual-task method proved to be significantly better at improving speed, stride length and cadence for both dual-task and single-task tests. Combining walking and cognitive tasks improved the patients cadence and dynamic gait index, which describes balance while walking, in single-task tests. It was also found that combining balance and cognitive or motor tasks improved a number of balance measures significantly compared to single-task training [34]. Despite the outcomes reported in [34], the conclusion is that more studies are needed in order to support that dual-task training improves performance in dual-task tests. The review study shows that a dual-task approach improves single-task tests compared to the single-task training [34].

It also has been found that training rhythmic arm and leg cycling can help improve gait in stroke patients, despite the training not being based on gait. A study by Klarner et al. [35] subjected stroke patients to arm and leg cycling training for a period of five weeks, and concluded that the majority of the participants improved their gait ability significantly. Another study found that arm cycling alone could also help improve the walking ability [25] thereby showing that the rehabilitation should not necessarily focus solely on gait specific training.

An approach similar to both dual-task and arm/leg cycle training can be seen in studies where

Tai Chi was used as a rehabilitation method for stroke and Parkinson's disease patients, implementing the aspect of thought, simultaneous movement and non-gait based training into the training [33, 12]. This use of martial arts training resulted in multiple studies finding significantly higher improvement in balance compared to the control groups, while gait measures did not improve significantly with the implementation of Tai Chi training [33]. These findings indicated that martial arts could help increase balance in stroke patients [33]. It was also found that Tai Chi helps to reduce the number of falls for people suffering from balance problems after both stroke and Parkinson's disease, while in this study it did not result in a significant difference between balance measures compared with regular treatment [12]. It has also been found that Pilates training improves both static and dynamic balance in older adults compared to the control group that only did their normal daily activities [11].

2.5 Problem definition

The previous chapter introduces the problem of patients suffering from complication of mobility caused by stroke or SCI and leads to the current rehabilitating methods used to train patients to regain mobility. However, these methods are not standardised and evaluations of patient performance is subjected to physicians personal experience and patients immediate feeling. Additionally, most evaluations occur in clinical environments when performing simple movement tasks, which translate poorly to real life.

It can be discussed whether or not current rehabilitation training with single-task training of simple movements is properly prepares patients to live independent daily lives post rehabilitation. This project propose that training involving advanced dynamic movements can further improve on patients strength and balance, better preparing them for daily life, when compared to traditional simple movement training. However, there exist no suitable system to evaluate advanced dynamic movements. Thus a new system is needed to have a way to measure and assess patients ability to perform advanced dynamic movements to determine if this type of training is an improvement to current rehabilitation methods.

This leads to the following problem definition:

How can a wearable system, capable of measuring balance performance during advanced dynamic movements, be developed?

3 | Methods

For this project reaction and pressure forces were collected from subjects performing the karate kata Pinan Nidan. A karate kata is a sequence of detailed choreographed patterns of movements. Many different types of kata exist, each practice visualisation, balance and basic technique through repetition of movements. Different katas have different sequences of movements, some are more difficult than others where jumps and kicks are part of the movements. For this projects data acquisition the kata Pinan Nidan is chosen. Pinan Nidan consists of a series of movements involving steps, turning and hand strikes, where the performers' feet are on the ground at most times. Pinan Nidan takes between 30 and 60 seconds to perform depending on the speed of movements. The kata consists of 13 stepping, 11 turning, 7 punching and 13 blocking movements [36].

3.0.1 Subjects

Three healthy test subjects were included in this study; one who is a master at karate (+30 years of karate experience), one intermediate (3-5 years karate experience) and one novice (less than 1 year of karate experience). All subjects were able-bodied and had no neurological or muscular injuries. Subjects were prior to the test instructed about the purpose of the study and their role as test subjects.

3.1 Instrumentation

For this project data were acquired using gyroscopes and force sensors. The gyroscopes were provided through the use of the Shimmer3 device from Shimmer Sensing (Dublin, Ireland). Force sensors were from Interlink Electronics Inc. (California, USA) of the 400 Series.

The Shimmer3 device is a nine degree of freedom (DoF) Inertial Measurement Unit (IMU) possessing four different types of sensors; accelerometer, gyroscope, magnetometer and altimeter. The Shimmer3 is capable of being configured to enable or disable specific sensors depending on which is needed. For this project only the gyroscope module of the device will be used. The Shimmer3 device has dimensions of 51mm x 34mm x 41mm and is easy to place nearly anywhere on the body with elastic straps with snap clips. Two Shimmer3 devices will be used for this project.
The gyroscope is a MPU-9150, with a range of ±250 / ±500 / ±1000 / ±2000 degrees per second (dps). The gyroscope has sensitivity of 131 LSB/dps at ±250dps [37]. Communication between the Shimmer3 devices and the computer proceeded through Bluetooth (Bluetooth SIG, Washington, USA). The computer were running MATLAB (MathWorks, Inc. Massachusetts, USA) and the *Shimmer MATLAB Instrument Driver Library* to collect the streamed data from the Shimmer3 devices.

The force sensors used were Force Sensing Resistors (FSR) from Interlink Electronics, models

402 and 406. The FSR 402 is a 13mm diameter circle single-zone resistor capable of force detection in a range from 20g to 2kg. The FSR 406 is similar but covers a larger square area of 38mm $\times$ 38mm [38]. A total of six sensors was used with three sensors under each foot. An Arduino Uno was used for handling recording and saving the data from the FSRs. The Arduino Uno was mounted on a breadboard, and connected to six jack stick plugs, an microSD card reader and batteries for power supply (see figure 3.1). The FSRs were connected to the Arduino through 3.5mm jack sticks. Data collection was initiated by pressing a designated record button. When recording was active a LED on the board would light up. Data from the FSRs was stored on a microSD card and processed offline with MATLAB.

The system setup as a whole for both the gyroscope and FSR parts can be seen illustrated in a block diagram on figure 3.1.

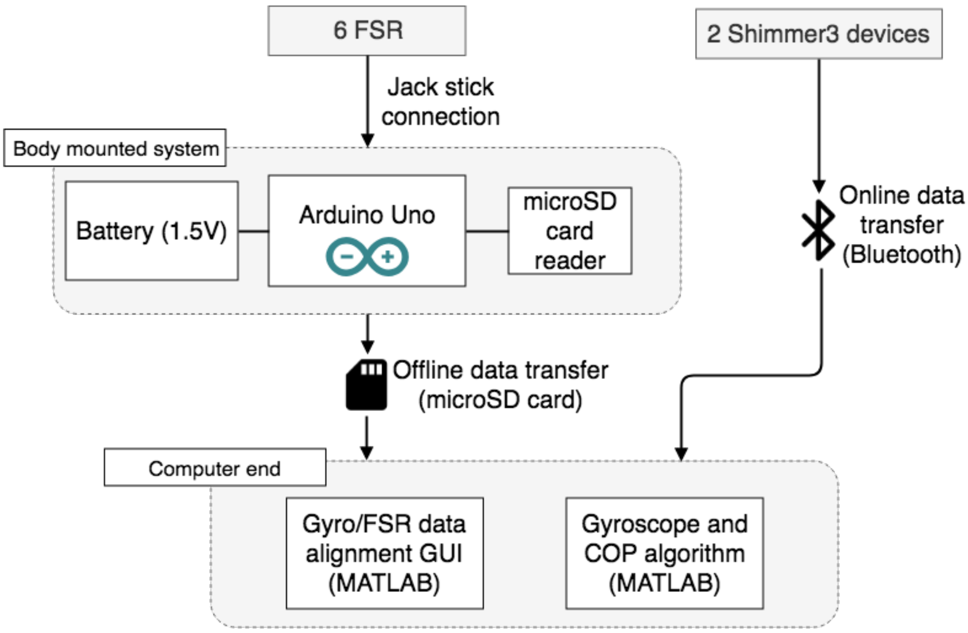

Figure 3.1: Block diagram of the system. The left side shows the pressure sensing part utilizing the FSRs. On the right side is the Shimmer3 devices (gyroscopes). All data was collected and processed on a computer using MATLAB.

3.1.1 Instrumentation placement

During data acquisition the subjects were wearing the instruments presented earlier in section 3.1. One Shimmer3 device was placed lateral distal to the knees on each of the subject's legs.

The FSRs were placed on the sole of each foot of the subject. One FSR 406 was placed at the lateral eminence of the sole. Of the two FSR 402 sensors, one was placed under the heel and the other at the medial eminence of the sole. The placement of FSRs can be seen on figure 3.2.

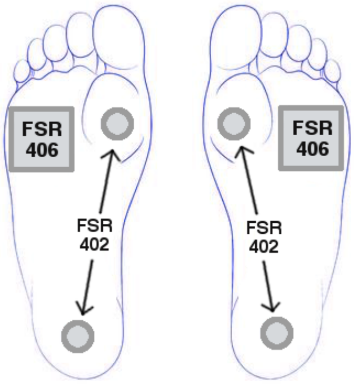

Figure 3.2: The placement of the FSR 402s and 406 under the foot of subjects.

The Arduino-setup was placed at the lower back of the subject and handled data collection. Collected data was stored on an microSD card for offline data analysis with MATLAB. An illustration of device placement on a subject is presented in figure 3.3.

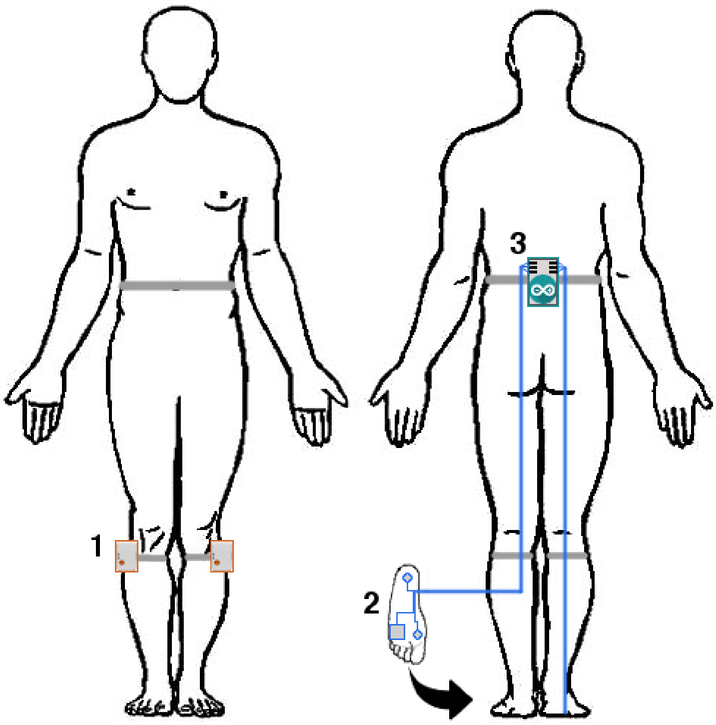

Figure 3.3: The placement of the Shimmer3 IMU devices (1), FSRs under to feet (2) and Arduino-setup (3) on a test subject.

3.2 Data Acquisition

Data acquisition from both the FSR sensors and the Shimmer3 devices were set to have a sample frequency of 100Hz. This sample rate was used by others performing similar measurements [39, 40, 41]. Additionally, the sample rate were decided to be the same so it was possible to match the two data streams to each other, to enable comparing of measured pressure forces under the feet to movement of the body. A simple graphical user interface (GUI) was developed to match the data. This manual approach were favourable for this project as it was determined that it would be more time consuming to develop an algorithm to automatically match data streams. It would also go beyond the scope for the project.

Data from the Shimmer3 devices was sent and saved directly to MATLAB via Bluetooth.

For saving acquired data from the FSR sensors, an Arduino program was written to arrange measurements into $n \times 6$ matrices. Each column corresponded with the channel input for each FSR. See figure 3.4 for the numbering of FSRs and channels. Rows in the matrix were time steps. The data was saved to a *.txt*-file on the microSD card.

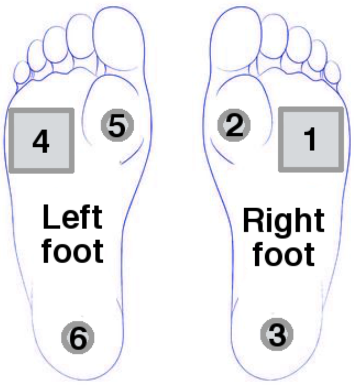

Figure 3.4: The numbering of each FSR sensor according to the channel they were recorded to in the Arduino program.

3.3 Data Processing

This section covers processing of acquired data. All data processing were performed using MATLAB.

3.3.1 Filtering

Acquired FSR data was filtered with a third order low pass Butterworth filter with cutoff at 5Hz, according to [42]. However, during the experiment it was observed that subjects dragged their feet over the ground when performing the kata. This was not anticipated, and an examination of acquired data showed noise artefacts in frequencies above 1Hz, associated with dragging the feet. As the goal for this study was to investigate subjects sway of balance during movements, and not directly determining movements, the cutoff frequency was changed to 2.5Hz.

Gyroscope data was similarly filtered through a third order low pass Butterworth filter, but with cutoff frequency set at 1.25Hz, according to [43].

3.3.2 Data Alignment

Because the measurements from the FSRs were run on an Arduino, and the gyroscopes ran through a Shimmer Sensing developed script for MATLAB, the timing for the measurements were run differently. In order to analyse FSR data to the corresponding time for gyroscope data a data alignment GUI was developed in MATLAB. The implemented alignment program was a simple GUI which created a plot where different channels from the six FSRs and six DoFs from the two gyroscopes (three for each on each leg) could be shown or hidden. Additionally each channel could be translated left or right. This enabled alignment of data from the FSRs to the gyroscopes, based on spikes in measurements caused by a small jump subjects were instructed to perform before and after performing Pinan Nidan. An example of the alignment GUI can be seen in figure 3.5.

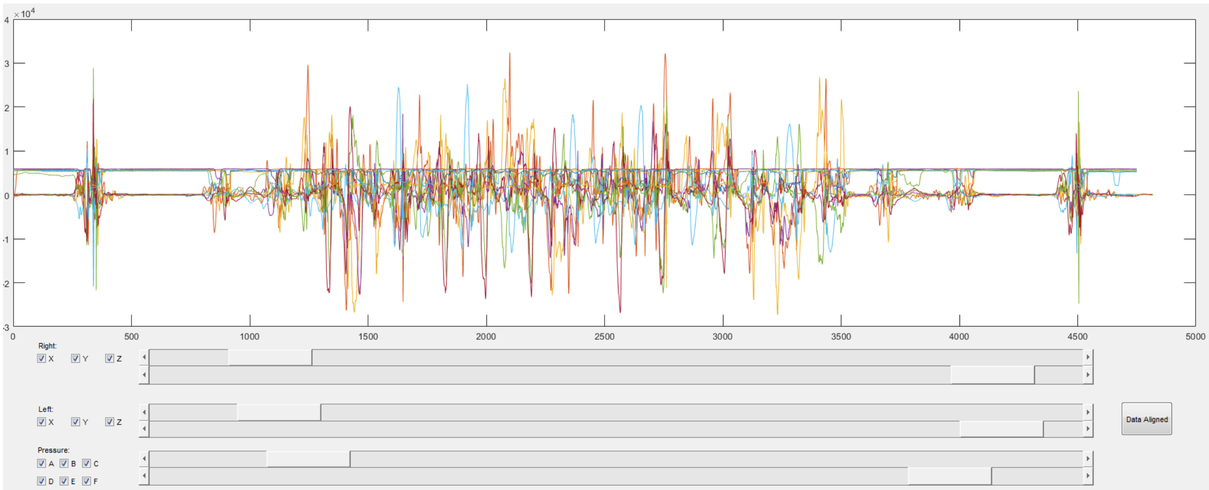

Figure 3.5: The alignment GUI showing a selected number of channels from the FSRs and gyroscopes. All channels can be translated in order to align timestamps for the FSR measurements to timestamps for the gyroscopes.

3.4 Data Analysis

This section covers the analysis of acquired data.

3.4.1 Calculation of Movement Scores

For calculation of a movement score four separate measures were calculated; length, span, velocity change and movement intensity. Center of Pressure (COP) was calculated for a test subject on a plane and used as base for the calculation of length and span measures. The length was calculated as the path of the moving COP during recording. Span was calculated as the area in which the COP has travelled. Velocity change was used as a measure for the frequency of the changes in angular velocity. Movement intensity was used to describe how fast a subject moved during the kata performance.

Calculation of Centre of Pressure

The COP calculation consisted of two simple equations to find the displacement of balance in the X and Y directions. To ensure the calculated values were unrelated to the weight of the test subject, but solely describes the displacement of balance, each calculation of the pressure distribution will be divided by the overall pressure placed on all sensors at that point. The COPx equation found the distribution of weight between the two feet, whereas the COPy equation describes the distribution between the sensors on the front and back of the foot. The COP measure was used in calculations of the length and span measures. A weight (W) was added to the pressure readings (P) to compensate for the displacement of the sensors in relation to each other and for the number of sensors on the front and back of the foot. The COP calculations for X and Y directions followed equation (3.1) and equation (3.2):

$$COP_x(i) = \frac{\sum_{i=1}^{3} P_i W_i - \sum_{i=4}^{6} P_i W_i}{\sum_{i=1}^{6} P_i W_i} \tag{3.1}$$

$$COP_y(i) = \frac{\sum(P_3W_3 + P_6W_6) - \sum(P_1W_1 + P_2W_2 + P_4W_4 + P_5W_5)}{\sum_{i=1}^{6} P_i W_i} \tag{3.2}$$

Calculation of Length score

The length of the COP outcomes was calculated and divided by the length (L) of the recorded data, so the outcome measure described the mean COP change between each sample. To ensure this measure had an effect on the final score it was multiplied by a factor of 10. The length was calculated individually for X and Y directions for later use in score calculation (see equation (3.3)).

$$Length_{x,y} = \frac{\sum_{i=1}^{L-1} \sqrt{(COP_{x,y}(i+1) - COP_{x,y}(i))^2}}{L} * 10 \tag{3.3}$$

Calculation of Span score

Calculation of the span described the span between the outer most points of the COP changes, giving the area in which the COP travelled. The span was calculated by taking the absolute value of the difference between maximum and minimum observed values of COP. This was calculated for both the X and Y directions. In the same manner as the length measure scaled by a factor of 10, the span measure was divided by 10 to decrease the effect of the span in relation to the other measures. Span was calculated as shown in equation (3.4):

$$Span_{x,y} = \frac{\left|max(COP_{x,y}) - min(COP_{x,y})\right|}{10} \tag{3.4}$$

Calculation of Velocity Change

The calculation of velocity changes processed the angular velocities as frequencies to determine the changes in angular velocities. A Fourier transform of the data showed the distribution of slow and fast changes of the angular velocity. Here, the divide between slow changes (frequencies: 0.01-0.625Hz) and fast changes (frequencies: 0.626-1.25Hz) are set at half the cutoff frequency used for filtering (1.25Hz). The fast changes were assumed to be caused by trembles at the legs done to correct and regain balance. Slow changes were hypothesised to only be caused by larger movements, such as steps or turns. Thus, the measure is an expression for how precise movements were performed. The measure was calculated by subtracting frequencies in the low category from the high category frequencies, and dividing by to sum of all frequencies, as shown in equation (3.5):

$$Change = \frac{LowFreq - HighFreq}{LowFreq + HighFreq} \tag{3.5}$$

Calculation of Movement Intensity

The movement intensity measure express how fast a subject could start and stop movements. The calculation divided the distribution of slow and fast movements, based on the measured angular velocity. The border between slow and fast was decided as the mean angular velocity measured for a full recording. This means that the faster a subject moved during the kata the higher the mean would be. This ensured that only very fast movements such as steps and turns were categorised as fast velocities, while slower movements such as those made during sways when regaining balance were categorized as slow velocities. The categorization of movements were calculated as shown in equation (3.7), where i is sample and j is the channel for each of the three gyroscope channels (x, y, z). Following, the calculation for movement intensity is as shown in equation (3.7), where L is the size of the gyroscope data matrix.

$$M(i,j) = \begin{cases} mean(Gyro(j)) < Gyro(i,j) = 1 \\ mean(Gyro(j)) > Gyro(i,j) = 0 \end{cases} \tag{3.6}$$

$$Intensity = \frac{M * |Gyro|}{\sum_{i=1}^{L} |Gyro|} \tag{3.7}$$

Calculation of Performance score

Each movement score; length, span and velocity change and movement intensity was used to calculate a final performance score for each subject. The performance score was calculated as seen in equation (3.8). The best performance score was produced by having a larger span relative to the length, as the performance score is better the lower the value.

$$Score = \frac{1 - Length}{Span} * (1 - Change) * (1 - Intensity) \tag{3.8}$$

3.5 Statistical Analysis

Following data processing, acquired data was either analysed through a one-way ANOVA or a Kruskal-Wallis test depending on if data have Gaussian, or non-Gaussian distribution respectively. To test the data distribution, a One-sample Kolmogorov-Smirnov test was implemented. Bonferroni correction is applied to the statistical outcomes, to avoid false negatives or positives when comparing three groups.

3.6 System test

This section covers the test of the system, prior to conducting the experiment for the project.

3.6.1 Method of Test for Gyroscopes

The Shimmer3 devices were calibrated using the built in function of Shimmer Sensing's program, Consensys, to ensure the devices would work as expected [37].

3.6.2 Method of Test for Force Sensitive Resistors

The FSRs were tested by placing a 1kg weight covering a surface area of $1cm^2$ applied in the middle of both types of FSRs. This was done to test if any of the sensors were broken or deviated from the values of the other FSRs.

3.6.3 Test Results for Force Sensitive Resistors

A weight of 1kg were applied to each FSR in order from FSR channel 1 to 6. The weight was applied for approximately five seconds to each FSR in the middle of the sensor area. Results of the FSR test is shown in figure 3.6.

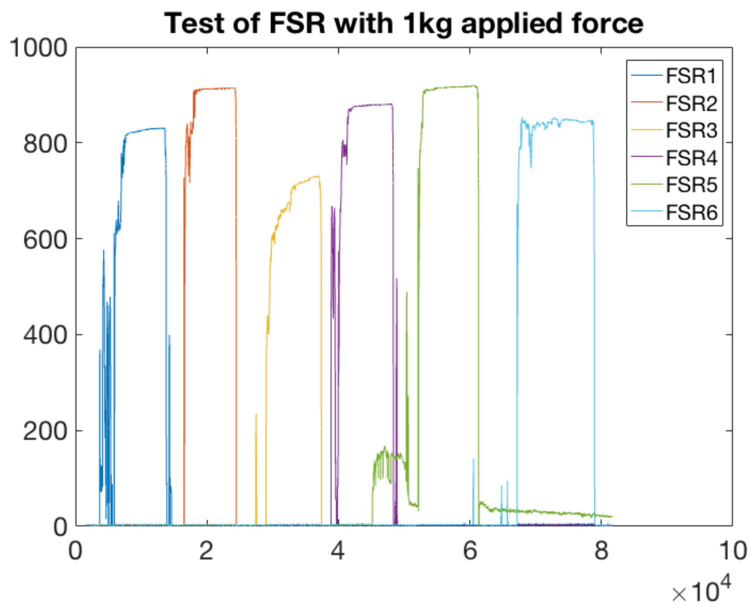

Figure 3.6: The result of the test of the six FSRs.

As it can be seen from the results none of the sensors were broken, however FSR number 3 (FSR3), located at the heel of the right foot, returned a lower resistance when applied a 1kg weight compared to the other FSRs.

This could prove a problem if data were to be compared between individual FSRs, however the output for each FSR sensors was used for estimation of a point for the subjects COP, which were be used to compare COP between subjects. Thus, the FSR3 measurement would not have an effect as long as FSR3 had the same deviance for every subject.

A later analysis of acquired data from the subjects performances showed that the readings FSR3 had small variance when compared to readings from the other FSRs. Figure 3.7 shows the mnaximum recorded values for each FSR during kata performance for all subjects. Here FSR3 recordings have little variance from other FSRs.

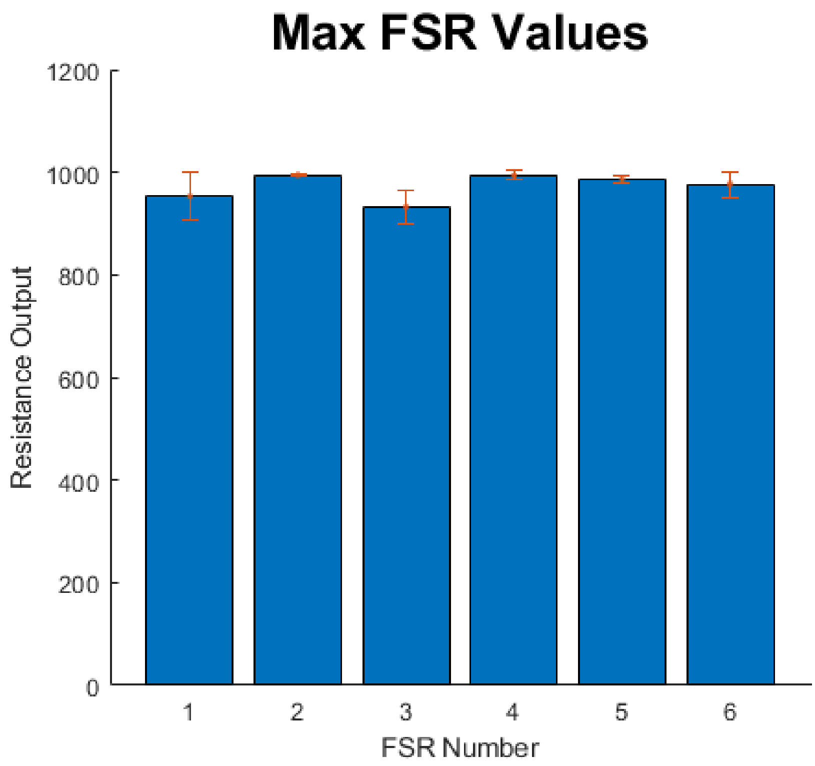

Figure 3.7: Barchart of maximum FSR recordings for all kata repetitions for all subjects.

3.6.4 System Test

The system as a whole was tested with a walk sequence. The sequence involved periods of no movement, movement by walking and turning and a light jump to mark the beginning and end of the sequence. The test walk sequence was as follows:

- 5 second pause
- Light jump
- 5 second pause
- Walk five steps
- 180 degree turn
- Walk five steps
- 5 second pause
- Light jump
- 5 second pause

Following the system test the acquired data was qualitatively evaluated to ensure everything worked as intended.

3.6.5 Results for System Test

Result of the system test as a whole were successful, despite lower readings from FSR3. Acquired data was plotted for each FSR channel, so the recorded output could be viewed alongside a video recording of the test walk sequence. At each step FSRs were reacting and returning values consistent with what would be expected when pressure was either applied to or removed from the sensors. It was concluded that, as the lower resistance returned from FSR3 was consistent for all data collection, the *"error"* would be present in each data set and therefore would not have any effect on comparison between subjects. Later analysis of data showed this to be correct.

3.7 Protocol

3.7.1 Aim

The experiment measured the ground reaction forces during the performance of the karate kata Pinan Nidan. At the same time gyroscopic sensors recorded the rotational forces of the legs for the following data analysis.

3.7.2 Design

Before the Experiment

- The data file “DATA.txt" on the microSD card for the Arduino will be emptied and the microSD card will then be placed in the Arduino-setup.
- Subjects have knowledge and various amounts of experience with the kata Pinan Nidan prior to the experiment. No subject needs instruction of performance of the kata.
- The subject is instructed that before recordings of the kata they will stand still for five seconds, do a small jump and stand still for five seconds. This small sequence is to be performed both before and after performance of the kata.

Initial Part

1. The person responsible for the test will mount the force sensors underneath the feet of the subject according to the labelling on the sensors. These sensors will be placed as following on both feet:
    - One FSR406 sensor on the lateral eminence of the sole
    - One FSR402 sensor on the medial eminence of the sole
    - One FSR402 sensor at the heel

2. 1 Shimmer3 device (gyroscopes) will be mounted lateral distal to the knee. One sensor on each leg.

3. The Arduino-setup will be mounted around the waist, and the system will be placed at the lower back.
4. Elastic straps will be mounted right above the knee to ensure the cables for the force sensors stays in place, and to mount the Shimmer3 devices.
5. The force sensors will be plugged into the Arduino-setup according to the numbering on both the system and the sensor cables.
6. Shimmer3 devices will be connected to MATLAB.
7. The subject will practice one round of Pinan Nidan to warm up.
8. The subject stands ready to begin performing Pinan Nidan with recordings.

Data Acquisition Part

1. Recording from the Shimmer3 devices will be initiated in MATLAB.
2. The Arduino system will be powered up and recording started by pressing the designated “Record” button until the red LED lights up.
3. Subject will be asked to stand still for 5 seconds then do a small jump, stand still for 5 seconds, do another small jump and then stand still for 5 seconds before moving on.
4. After this initial movement, the subject will be asked to perform the Pinan Nidan.
5. When the subject is done with the Pinan Nidan, they will be asked to perform a 5 second pause, small jump and 5 second pause again.
6. The recording is stopped by pressing the “Record” button until the red LED turns off. The Arduino-setup will be shut off and the microSD card removed from the setup to extract the data to a computer.
7. After data is transferred to the computer, the microSD card is inserted to the Arduino-setup, and the process continues from step 1 in “Data acquisition part”.

The subject will perform Pinan Nidan four times in total, one for practice and three where data is recorded.

Removal of the System

1. After the data acquisition the subject will be asked to stand still and the Shimmer datastream will be stopped.
2. At the same time the “Record” button on the Arduino will be pressed until the red LED turns of.
3. The Arduino-system will be turned off and all the sensors and the Arduino will be removed from the subject.

3.7.3 Participants and Statistical Considerations

The included three participants were selected based on their experience with the kata Pinan Nidan. This included a master (+30 years of karate experience), intermediate (3-5 years of karate experience) and novice (less than 1 year of karate experience). The number of participants was chosen as the study did not aim to find a strong statistical significant difference between the subjects, but rather aimed to examine if there was a way to determine the stability of the subjects during the Pinan Nidan.

The time for the experiment will be 45-60 minutes.

4 | Results

The outcome measures calculated for each subject can be seen in table 4.1.

	Novice	Intermediate	Master
Length	0.253 ± 0.043	0.293 ± 0.004	0.303 ± 0.040
Span	0.407 ± 0.008	0.415 ± 0.012	0.433 ± 0.045
Frequency	0.071 ± 0.043	0.062 ± 0.022	0.121 ± 0.014
Intensity	0.758 ± 0.013	0.775 ± 0.003	0.783 ± 0.003

Table 4.1: Outcome measures for each subject. Average measurement found over the three repetitions each subject performed.

The final performance score for each subject is presented in table 4.2.

	Novice	Intermediate	Master
Avg. Score	9.532 ± 0.292	8.579 ± 0.101	7.278 ± 0.891

Table 4.2: Performance scores for each subject

A Kruskal-Wallis test has been implemented for the statistical analysis of the scores and intensity measure, as the data comes from non-Gaussian distributed data, and the comparison was between three unmatched groups. The other measures came from a Gaussian distribution according to a Kolmogorov-Smirnov test, and a one-way ANOVA were implemented for these. The results from the statistical tests were analysed using Bonferroni correction to compensate for the comparison of three groups, and avoid false negatives or positives. The results of the statistical analysis are presented in table 4.3.

	Overall	N vs. I	N vs. M	I vs. M
Length:	0.243	0.382	0.249	0.933
Span:	0.316	0.936	0.318	0.472
Frequency:	0.095	0.925	0.170	0.105
Intensity:	0.039	0.549	0.030	0.295
Score:	0.027	0.372	0.020	0.372

Table 4.3: Statistical analysis p-values for comparison between subjects

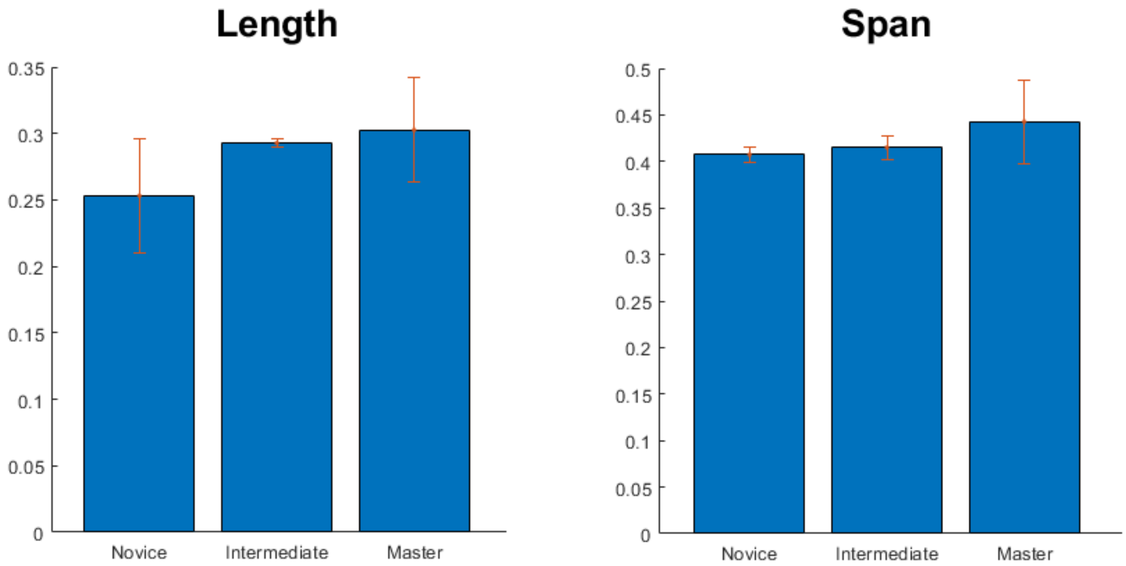

Figure 4.3: Barcharts of the lenght and span measures. No significant differences were found between subjects in either measure.

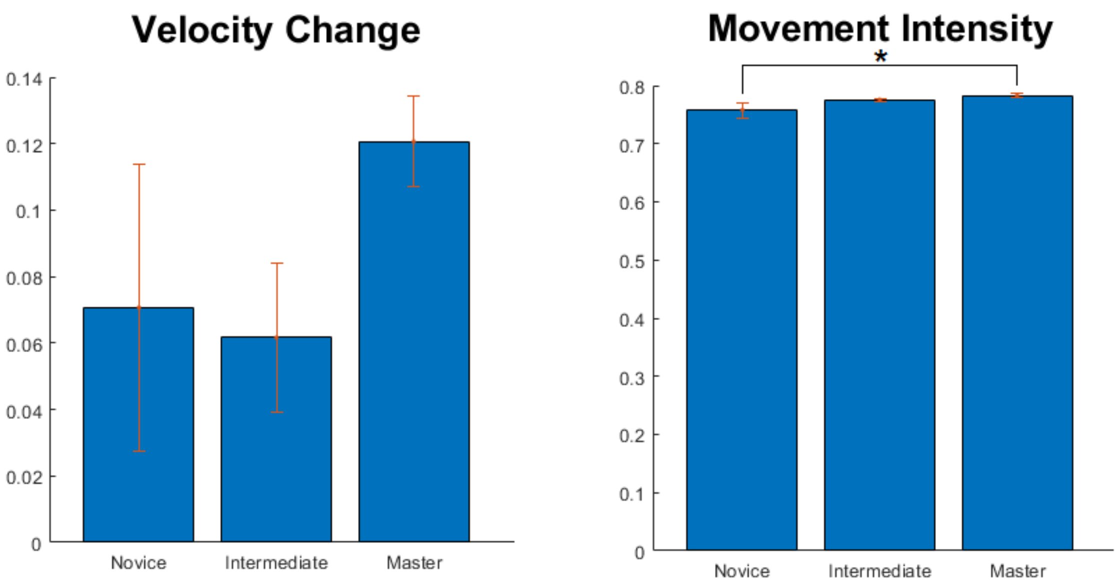

Figure 4.6: Barcharts of the velocity change and movement intensity measures. No significant differences were found between subjects in the velocity change measure. Significant difference was found between the novice and master subjects for the movement intensity measure.

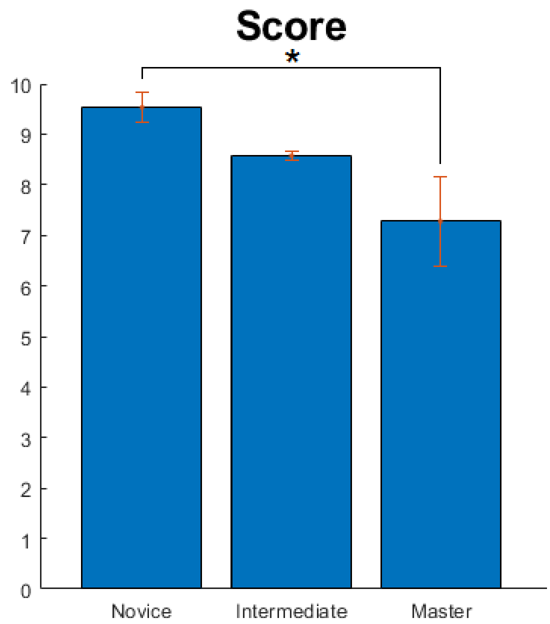

Figure 4.7: Barchart of the score between subjects. Significant difference was found between the novice and master subjects.

No significant difference was found within either of the length, span or velocity change measures. The intensity measure showed a significant difference ($p < 0.05$) between the novice (0.758 ± 0.013) and the master (0.783 ± 0.003).

The analysis of the scores showed a significant difference ($p < 0.05$) between the novice (9.532 ± 0.292) and the master (7.278 ± 0.891). Otherwise no difference was to be found within the scores.

5 | Discussion

The expected results was that the master subject with the most experience in karate would achieve high scores, followed by the intermediate with second highest results and novice achieving the lowest scores. This was reflected by the scores, where the master (7.278 ± 0.891) had a significantly higher score ($p < 0.05$) than the novice (9.532 ± 0.292), while there was no difference between the intermediate and the novice or the master. This was caused by a combination of the different measures, where the most influencing measure was the intensity. This outcome measure yielded a significant difference ($p < 0.05$) between the novice (0.758 ± 0.013) and the master (0.783 ± 0.003), and was the main reason for the different score outcomes, along with small variations in the other measures. The reason for this could be that the novice subject sways more when stopping a movement and has to regain balance, while performing slower and less intense movements as well, leading to a lower intensity score. This does not necessarily indicate the level of skill when performing the kata, but it shows the novice was not as stable and does not perform as explosive movements during the kata compared to the master.

During the test of the system a problem occurred with one of the FSRs used for measuring pressure distribution during the kata performance. The test of the FSRs showed that FSR3 returned lower values than the other sensors. This was most likely caused by the fact that the FSRs used in the project were used in another study as well. This problem has been highlighted by Hall et al. [44]. As the FSR data was not used for comparison between FSRs and the deviation in measured resistance was consistent for all measurements, it was assumed that it did not have an effect on the final outcome. However, a consequence of this is that the measures in this study cannot be compared to other studies implementing the same methods, as the FSR readings would differ from this study. However the relation between the measures is still relevant for comparison.

A shortcoming of this study is that few subjects were recruited. This provided less evidence for the study results, but the study was meant as an initial process in the research area of investigating new methods for development of wearable systems to use in rehabilitation programs utilizing advanced dynamic movements in place of traditional treadmill gait training. This study aimed to prove the concept of developing a simple wearable system, in comparison to more advanced and costly techniques such as kinematic motion analysis.

The authors suggest that future studies should investigate the methods presented in this study in relation to kinematic motion analysis outcomes. This could be done in order to quantitatively evaluate the method of this study, when no similar studies, utilizing FSRs and gyroscopes, have yet been conducted.

In addition to this study, future studies could include the use of accelerometers to further expand on ways to analyse motion. Accelerometers could be used to investigate movement in translational axes, and not only rotational axes as in this study, as well as give a more precise indication for when and how movement occurs. Additionally, more sensors could be included to acquire more data. Other studies have used several more FSRs under the feet [45, 46].

Future studies should further investigate the use of martial arts as training in rehabilitation. Few studies have investigated the effect of training with martial arts or similar training including more advanced dynamic movements training [12, 33], however these studies have suggested improvement in patients strength and balance. It should be investigated further if this type of training alone or combined with traditional treadmill gait training currently used in rehabilitation programs could improve the outcome of the rehabilitation.

6 | Conclusion

This study proposed a novel method of measuring balance during advanced dynamic movements, and found a significant difference between test subjects with different skill levels within the performed kata. The results suggested that there was a relation between the length and the span of the Center of Pressure, where a high length within a low span was a sign of bad balance, while a low length within a high span showed the subject had control of balance. At the same time, the frequency distribution and intensity of gyroscopic data was found to be related to the intensity and precision of the performed movements. This study concludes that balance is improved with experience in karate when performing the kata Pinan Nidan. However, as this study is a pilot study with the proposed method, further studies should be conducted to conclude if a system like the proposed can be used to quantify advanced dynamic movements.

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