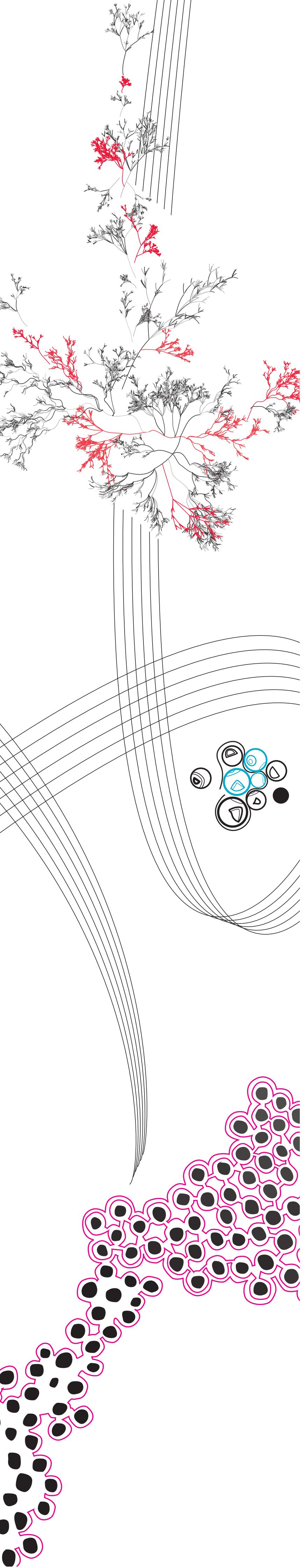

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BACHELOR ASSIGNMENT

REAL-TIME INERTIAL SENSOR-DRIVEN BIOFEEDBACK ON FOOT PROGRESSION ANGLE

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Abstract

In this study, a near real-time biofeedback system was developed, using inertial motion capture and augmented reality (AR) glasses. The system is designed to give feedback on foot progression angle (FPA), commonly used in gait interventions for knee osteoarthritis patients. Through alterations of this angle, mechanical loading on the knee joint can be reduced. By doing so, disease progression is slowed down and patients are able to lead daily lives with reduced physical pain. With the use of mixed reality technology glasses and inertial motion captures of the body, the system is able to provide patients with interventions in an ambulatory setting, in contrast to that of the current clinical research practices which use treadmills and cameras.

Through two rounds of experimental testing of the prototype (with four healthy participants altogether), the usability and effectiveness of this system are evaluated by using gait analysis and the System Usability Scale (SUS). Experimental results of the system prototype show that the system is usable, although there is still much to be improved regarding system performance and accuracy. Further research and development should be done before it can actually be deployed for use with knee osteoarthritis patients. Nevertheless, the proposed system could enable wider adoption of gait retraining rehabilitation applications by reducing complexity and cost.

Keywords: gait analysis; visual biofeedback; inertial motion capture; foot progression angle; wearable technology; knee osteoarthritis

Contents

Chapter 1

Introduction

Osteoarthritis (OA) is a chronic disease that is commonly affecting the world's aging population, especially in developed countries [1]. The disease is often found to affect the hip and knee and is a cause of pain and disability [2, 3]. According to the World Health Organization, OA is prevalent in ten to fifteen percent of people over sixty years old. By 2050, it is estimated that diseases like OA will affect 130 million people around the world. Out of the said population, forty million are severe cases of disability [3]. This degenerative disease affects patients and their relatives in their daily lives by lowering productivity levels, which in turn leads to financial burdens [4].

Currently, multiple interventions have already been developed for knee osteoarthritis (KOA). These interventions can range from lifestyle changes to pharmacological to surgical, although the latter are only considered in severe stages of the disease, while pharmacological interventions only address the symptoms [5]. Thus, non-invasive and non-pharmacological interventions are desirable for preventing progression of the disease. Examples of these interventions are weight management programs, changes in footwear, use of knee braces, rehabilitation for muscle strengthening, and gait training [6, 7]. These biomechanical interventions directly target the mechanical loading on the knee joint, which is one of the causes of the disease [6].

Gait training can be used to improve the walking style of a person in such a way that the body suffers less consequence and pain. For a person with knee osteoarthritis (KOA), the way in which one walks determines the biomechanical loading on the knee joint. Since it is difficult to determine the amount of contact forces between the bones in the knee joint without using invasive techniques, other measures have been used to target the reduction of these forces [6].

The knee adduction moment, in which torque is generated around the knee at the frontal plane, has shown to be highly correlated with the internal forces of the knee joint; thus, this variable is used in experiments of gait training with patients of knee osteoarthritis [8, 9]. Among others, walking styles with toes pointing inwards or outwards [10, 11], or controlled foot progression angle (FPA), have been identified from prior research to decrease load on the knee joint and have been taught to patients in interventions using (near) real-time biofeedback systems [12]. This intervention has helped to decrease pain for KOA patients and slowed down the progression of KOA [13, 14].

Even though gait training is beneficial, interventions are highly dependent on complex and expensive laboratory environment systems. To allow for wider clinical rehabilitation uses, inertial measurement units (IMU) can be used instead of optical systems, while still maintaining high accuracy and allowing for better portability and lower costs [15]. In addition, using IMU in combination with augmented reality glasses allows for an ambulatory system. However, the effectiveness of using inertial data from just the foot ankle for visual biofeedback in gait training is currently unknown.

There are multiple ways in which biofeedback can be provided, such as through visual representations, auditory reinforcements, or haptic (tactile) communication. Most previous research on feedback for gait analysis uses haptic feedback. In Shull et al.'s review from 2014 on the wearable feedback for gait analysis, the touch sensation was found to be used most often for giving feedback from wearable technology, followed by audio and visual feedback [15]. From previous studies that have used visual feedback for gait analysis, some with the combination of audio feedback, results have proved to be successful in gait training [14, 16, 17, 18]. The visual feedback used in these studies were often given through a large stationary screen in front of a treadmill. Visual feedback allows for quantitative feedback, which is preferred over qualitative feedback, as it allows subjects to comprehend details of how far from the target he or she is. With recent technological advances, such as Google Glass, Epson Moverio, and Microsoft HoloLens among others, ambulatory visual feedback has been made viable.

Although using a system of IMU sensors and augmented reality glasses may seem to be ideal for gait training, the usability is still yet to be known. The goal of this study is to test the usability and effectiveness of a near-real-time, AR glasses-projected biofeedback system on the foot progression angle, driven by IMU input. This will be done through gait analysis and through the use of the System Usability Scale (SUS). The hypothesis is that this ambulatory system will be usable.

Chapter 2

Development

2.1 System design

The components used in this system are the Xsens MVN Awinda Inertial Motion Capture Suit [19], Xsens MVN Studio [19], Unity Game Engine [20], and the Microsoft HoloLens Augmented Reality Glasses [21].

The requirement for the system as a whole is that user can move freely in any given direction. Further requirements can be found in the design of the visualization for FPA feedback.

The hardware of this system is composed of an inertial motion capture suit (Xsens MVN Awinda) and a pair of augmented reality glasses (Microsoft HoloLens). The combination of these two instruments helps to create an ambulatory system.

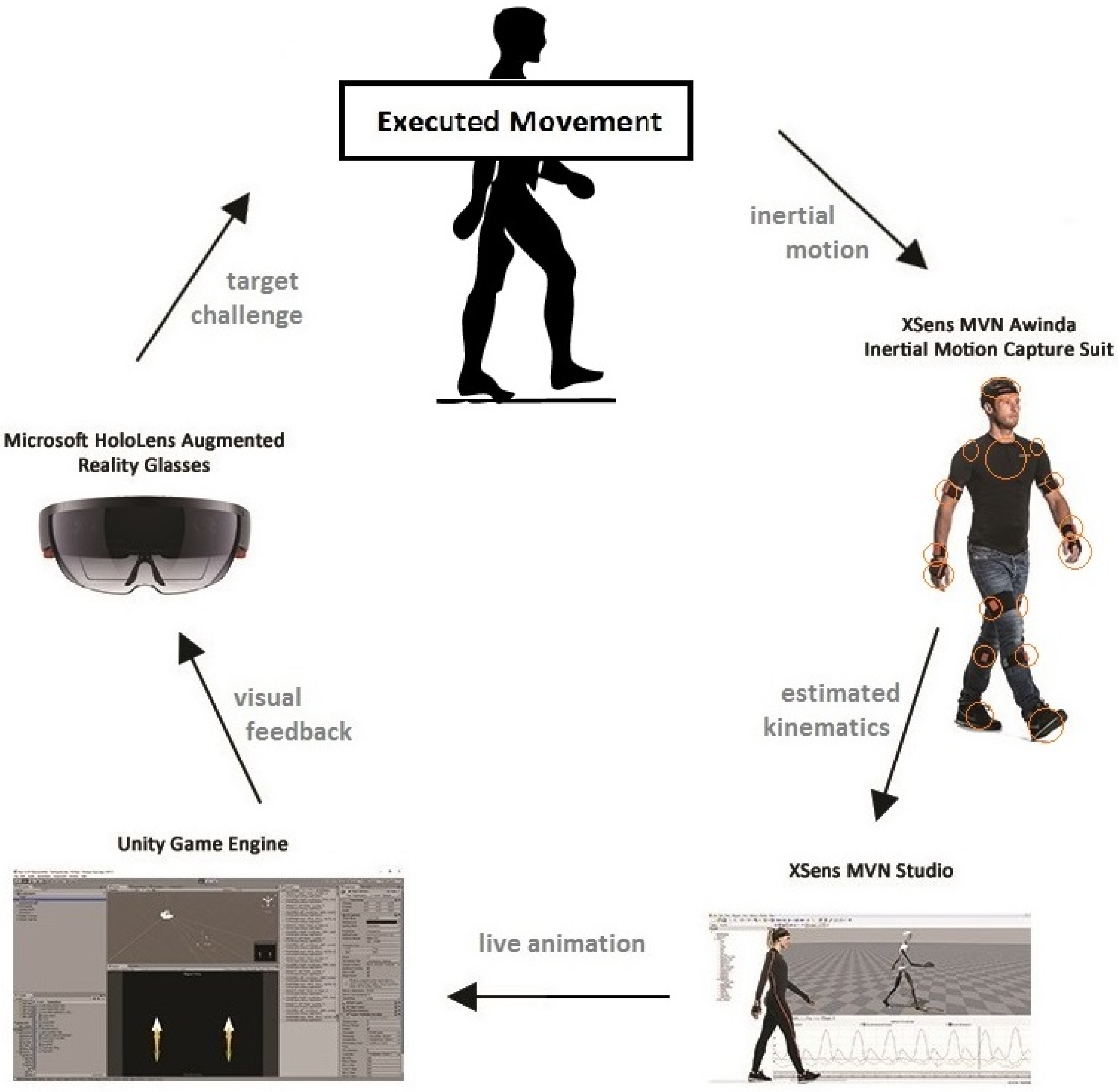

Figure 2.1: System schema. *Overview of the system as a whole and how data is retrieved and transferred from the sensors to the users augmented reality glasses.*

The MVN motion capture suit uses 17 IMUs to estimate the kinematics of the full-body (7 IMUs for only lower-body). These IMUs were placed in the following body segments: head, shoulders, sternum, upper arms, wrists, hands, pelvis, thighs, shanks, and feet. The kinematics estimations of these body segments are sent to the Xsens MVN Studio, in which the movements are modeled into a full-body kinematic model.

With the use of the Xsens MVN-Unity plugin (MVN Live Animation) [22], the motion captured from MVN Studio can be transmitted real-time to Unity Game Engine, which was used to build the biofeedback visualization. The sampling rate is 60 Hertz. A script has been developed in C# to calculate the FPA within the Unity application, according to input from MVN. Unity was used instead of other game engines because of its compatibility with both the Xsens products and Microsoft HoloLens glasses. Unity also has a lot of learning resources available and its open-source possibility for development makes it a preference over other game engines.

Through holographic emulation, the biofeedback from Unity can be displayed directly on the HoloLens glasses. With the augmented reality glasses, users are able to walk without any obstruction to their sights. With the biofeedback and targets provided through the visualization, users can proceed to alter their gait through changes in foot progression in such a way that targets are achieved. Feedback is given during the swing phase of user's gait and is given on the foot progression angle calculated when user is near stance phase (see Figure 2.3 visualizing gait cycle phases during walking).

All calculations and visualizations of this system are designed to run near real-time. The system as a whole, hardware and software, and how they are all connected can be seen in Figure 2.1.

2.2 Calculating foot progression angle

Foot progression angle (FPA) θ_{FPA} is the angle of the foot with respect to the walking direction on the transverse plane (x, z) and is defined in equation 2.1 below. The FPA gives feedback on the previous step taken. This is visualized in Figure 2.2. All calculations for FPA are done separately for the left and right foot (right FPA calculated with only right foot positions and left FPA calculated with only left foot positions).

$$\theta_{FPA} = \theta_{walk} - \theta_{foot} \tag{2.1}$$

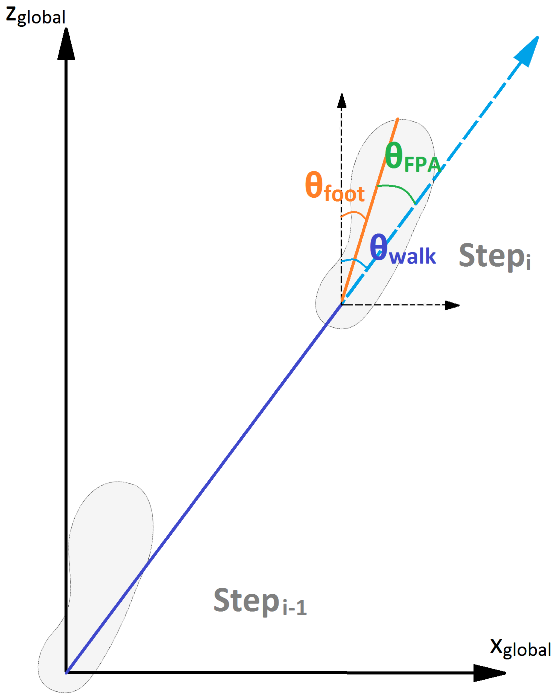

Figure 2.2: FPA calculation steps. *Calculation of angles from footstep on the transverse plane.*

Step detection

As FPA is calculated by using positional data of when the foot is approximately flat with respect to the ground, it is important to be able to detect when a step has been taken for each foot. Thresholds (shown in Figure 2.4) were used to get the positions at which the foot is considered down. These positions were then averaged. The stance in which one foot is fully flat on the ground, known as midstance is usually at around 30 to 40% of the gait cycle [23, 24]. The phases of gait cycle can be seen in Figure 2.3. With the thresholds used for velocities and heights of foot and toe, the average position of the foot was at around 45% of the gait cycle. This was used to create a state machine that was implemented into the script for detecting steps, as can be seen in Figure 2.4. Each time the conditions for each foot falls under the set thresholds, a step is counted for that foot.

Walk angle

The walk angle θ_{walk} is defined as the angle of the two-dimensional vector between two consecutive steps of the same foot $\mathbf{v}_{walk,i}$ (see equations 2.2 and 2.3). The position p_{foot} of each step is the average position of when the foot is down on the ground, as explained in the previous section. This calculation is done with the previous two steps, i and $i-1$, and is performed as soon as the foot is no longer down.

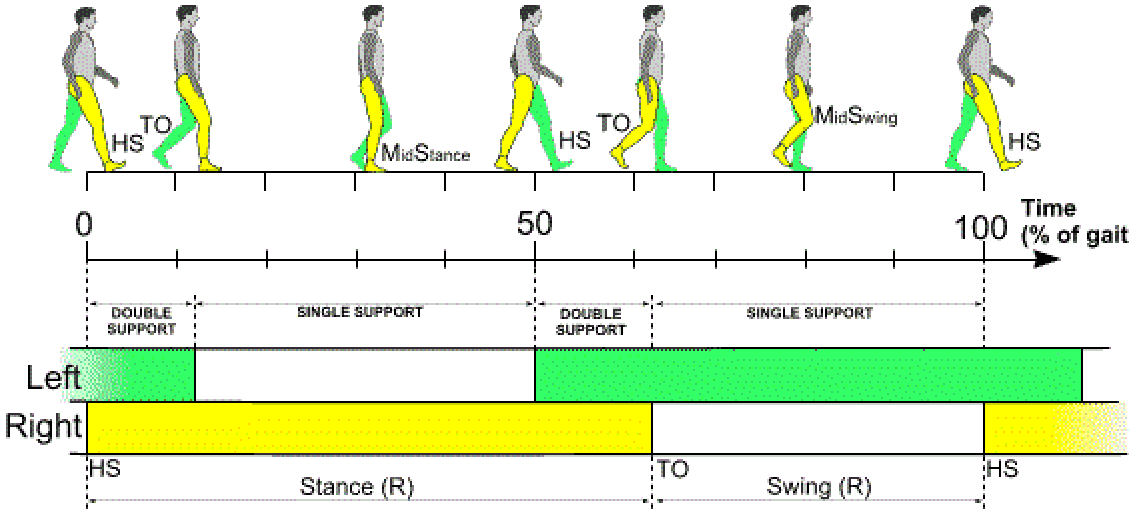

Figure 2.3: Gait cycle. *This diagram shows the phases of a person's gait while walking [25].*

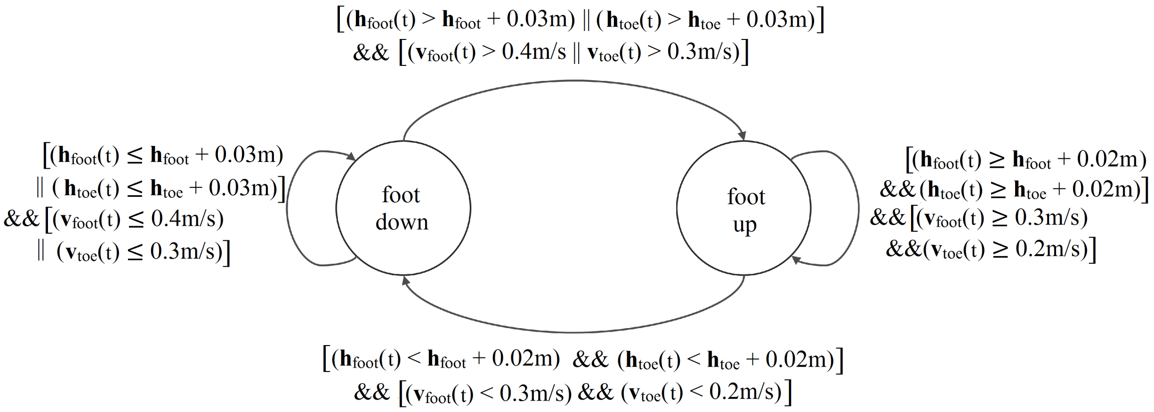

Figure 2.4: Foot state machine. *State machine for detection of footsteps, using thresholds for heights and velocities of foot and toe. Adapted with permission from [26].*

For step i when foot is down:

$$\mathbf{v}_{walk,i} = \mu(p_{foot,i}) - \mu(p_{foot,i-1}) \tag{2.2}$$

$$\theta_{walk} = \frac{180}{\pi} \cdot \arctan(\frac{\mathbf{v}_{walk,i_z}}{\mathbf{v}_{walk,i_x}}) \tag{2.3}$$

Foot angle

The foot angle θ_{foot} is defined as the two-dimensional vector from the ankle joint position pos_{ankle} to the toe position pos_{toe} as modeled in MVN at the time when the foot is flat on the ground (see equations 2.4 and 2.5).

For step i when foot is down:

$$\mathbf{v}_{foot,i} = p_{toe} - p_{ankle} \tag{2.4}$$

$$\theta_{foot} = \frac{180}{\pi} \cdot \arctan(\frac{\mathbf{v}_{foot,i}}{\mathbf{v}_{foot,i}}) \tag{2.5}$$

2.3 Visualization design

As stated, the visualization for the FPA feedback was created in Unity Game Engine. The requirements of the visualization were defined as follow:

- Make sense without explanation;

- Give feedback on foot progression of user in angles
  (*the feedback should be given in angles as it allows for intuition*);
- Provide a target goal for user, in which users should be able to comprehend how far away they are from the target;
- Provide user with a sense of immersion [27]
  (*This sense of immersion keeps the user motivated to achieve the target FPA*).

Other than the requirements for only the visualization, there are also functional requirements for the overall set up regarding the visualization:

- Visualization must be displayed in an ambulatory system;
- User must be able to properly understand orientation of visualization when undergoing any body movements (orientation of visualization must adapt to follow projection-headset and not move with respect to it);
- Feedback must be near real-time.

These requirements were taken into account for the visualization in Figure 2.5.

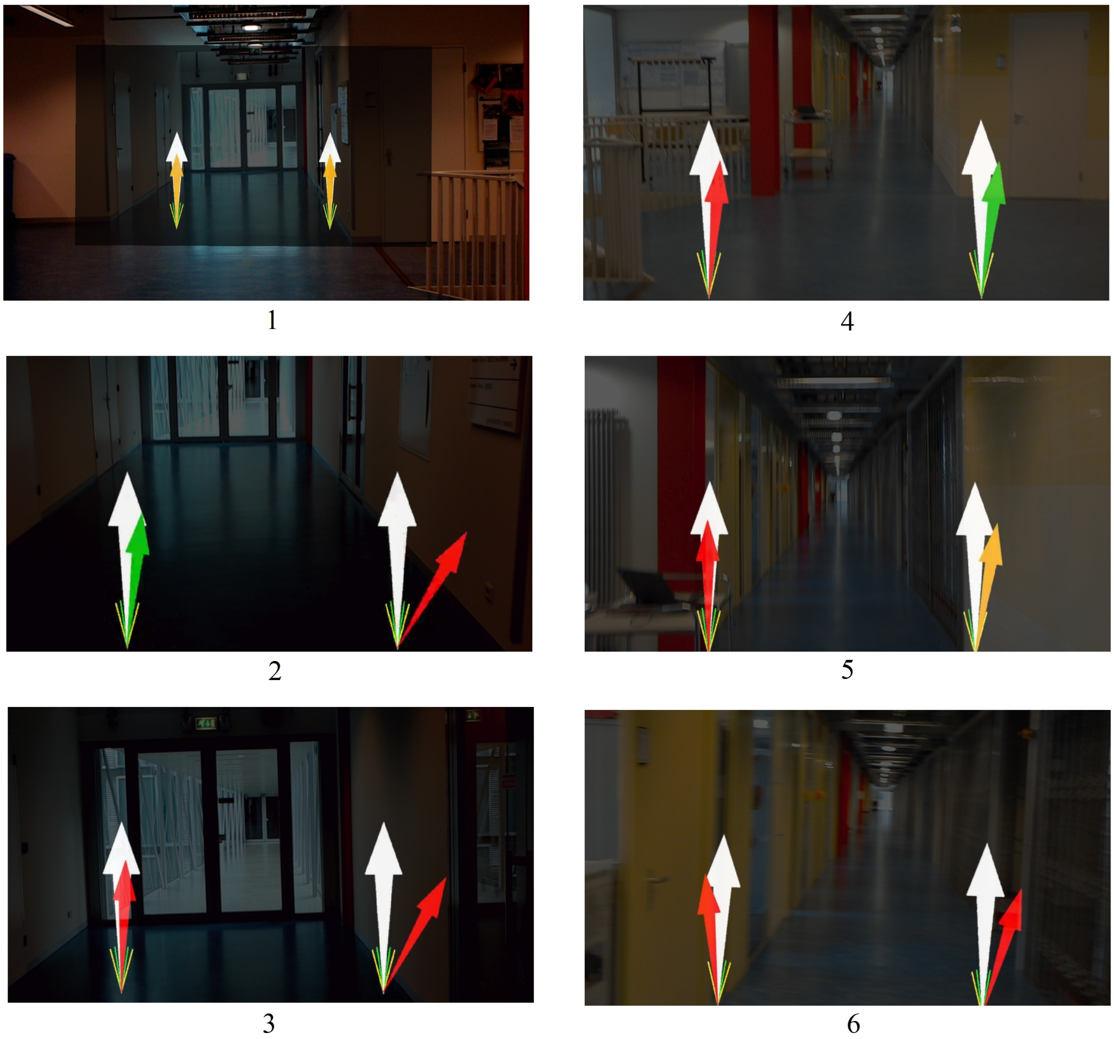

Figure 2.5: Example of deployed visualized biofeedback. *The smaller arrows are dynamic throughout each trial and provide feedback on FPA from the previous step; the larger arrows are the target arrows that remain static throughout each trial and is present for users to try to manipulate the smaller arrows in such a way that it aligns with the target.*

As can be seen from Figure 2.5, the color of the feedback arrows would change according to the calculated FPA. This was supposed to be an extra aspect to the feedback, which would allow the users to comprehend how well they are doing at achieving the target. This aspect of the visualization did not always display the correct range of colors and would need further optimization and development. Apart from this, small stationary lines of different colors can be seen at the pivot point of the angle. These lines signify the range of the area that the feedback arrow has to be in to fall under the “green”or “yellow ”range. If the arrow falls within the green range, then the step is considered to be good.

The placement of the visualization in augmented reality was also taken into account. The visualization is set 3 meters away from the user’s sight, such that it is not too far and not too close. If it is too close, the user is more susceptible to motion sickness [28]. If it is too far, the visualization displayed will not be stable, as the visualization stability is sensitive to head tilts. If the visualization is unstable, it could be hard for the users to understand and focus on the feedback provided. The distance between the feedback on the left and right foot is about hip width apart. This width was chosen, as it is also not too far apart and not too close together. If the feedback of the feet is too far apart, then it is difficult to maintain sight on the feedback for both feet. If it is too close together, the feedback will be in line of sight, obstructing the user’s view while walking.

Chapter 3

Methods

After the prototype has been developed, participants were recruited and experiments were performed.

3.0.1 Participants

Healthy individuals were recruited from the University of Twente. Inclusion criteria applied were: (1) 18 years or older; (2) does not require the use of eyeglasses for walking; and (3) no recent history of lower limb injury and can walk without any pain in any areas. All participants provided consent, signed on informed consent documents.

This experiment was approved by the Ethics Committee of the Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS). The protocol for the experiment can be found in Appendix A.

As the experiment was a first-stage prototype testing, healthy participants were used rather than actual patients with KOA. The assumption was that if gait training can be performed with healthy individuals, then it should also be feasible for those who are diagnosed with KOA.

3.0.2 Experimental design

For setup, a full-body configuration of the Xsens MVN Awinda suit was used with Xsens MVN Studio Beta Version 4.97.1. As this beta version of the MVN Studio was incompatible with the lower-body configuration, the full-body configuration was used, despite the upper-body segments being unnecessary. The lower-body configuration has also been experimented with the latest official release (Xsens MVN Studio version 4.4.0) but was deemed unsuitable due to difficulties with magnetic interference, especially for sensors that are close to the floor. This made MVN Studio 4.97.1, a newer beta version, more robust for the situation.

Table 3.1: *Placement of IMUs [19]*

IMU Location	**Placement description**
For lower-body configuration:	
Pelvis IMU (x1)	on posterior side of the pelvis approximately on the L5/S1 joint
Thigh IMU (x2)	on the lateral side of the thigh approximately on the middle point between hip and knee joint
Shank IMU (x2)	on the anterior/medial side of the shank 5-10 cm below the knee joint (medial surface of tibia)
Foot IMU (x2)	on middle of bridge of foot
For full-body (add on to lower-body configuration):	
Sternum IMU (x1)	on middle of chest
Shoulder IMU (x2)	on scapula
Head IMU (x1)	anywhere on head in headband
Upper arm IMU (x2)	on lateral side above elbow
Wrist IMU (x2)	on lateral flat side of wrist
Hand IMU (x2)	on backside of hand

By means of velcro straps, 17 IMU sensors were attached to the participants. The locations in which the sensors were attached can be seen in Table 3.1.

Apart from the motion capture suit, participants also had on the Microsoft HoloLens augmented reality glasses, which will allow them to see proper feedback in the appropriate trials. Participants were informed of which arrows were target arrows and which ones were giving feedback on their foot progression. They were also instructed to aim to match their FPA with the target angle as often as possible.

Table 3.2: *Trial progression of gait training intervention*

Trial	Target FPA	Target FPA Angle	Distance
Baseline	none	-	2×70 m
1	Large toe-in	$-5°$	2×70 m
2	Slight toe-in	$0°$	2×70 m
3	Slight toe-out	$10°$	2×70 m
4	Large toe-out	$15°$	2×70 m
Washout	none	-	70 m

An N-pose and walk calibration was used in Xsens MVN Studio 4.97.1. This procedure was used to find the alignment between the sensor and body segments to enable the inertial motion capture task. Next, the participants were instructed to walk approximately 70 meters along a corridor and back. Thus for each trial, each participant walked approximately 140 meters. Prior to every trial, subject started off with feet in N-pose position, as calibration was done for the Unity application. This calibration was needed to define the height thresholds used in the step detection algorithm on each trial. After each participant's baseline has been recorded, four different trials, each containing different target FPAs (-5, 0, 10, and 15 degrees), were performed (see Table 3.2). These four target angles were chosen as previous research studies have reported baseline FPA in healthy people of approximately 3 to 5 degrees [15]. Thus, the first and last trials with targets were expected to be more difficult than the second and third trials. The feedback was projected through the HoloLens and the first two trials required the participants to walk with toe-in, while last two trials required toe-out walking.

Participants were allowed to walk at their own desired pace throughout the experiment. Recordings were done for all trials through both MVN Studio and Unity. After each trial, the calibration in MVN Studio was checked to make sure if the modeled feet is still acceptable and not distorted. Once all the trials have been completed, the participants were instructed to walk normally again to remove any effects that may have been caused by the experiment (*washout trial*).

From the gait analysis, the data collected are: (1) positional data of foot and toe of both feet; (2) average position for each step for both feet; (3) step count for each foot; (4) calculated walk angle, toe angle, and foot progression angle of each foot.

3.0.3 System usability assessment

Upon completion of the experiment, the participants were asked to fill in the System Usability Scale (SUS) questionnaire (see Appendix B).

The SUS is a standard usability evaluation tool by John Brooke [29]. This instrumental tool was developed with the usability measures of effectiveness, efficiency, and satisfaction. Effectiveness is determined by how well the users are able to complete tasks with the system at hand. Efficiency is the amount of resources necessary for the tasks to be performed. Satisfaction is the user's perception towards the system upon use. With ten items evaluated on a five-point scale, subjective data of subject's perceived usability can be collected. The standard questionnaire used is reliable and valid even when used on smaller sample sizes.

3.0.4 Data processing and analysis

To get insightful data, the recordings from Unity's debugging tool were processed. The text files were pre-processed with Notepad++ to remove any lines with irrelevant information. Then a Matlab script was used to extract the values from the text file and store them as arrays. Another script was then used to perform statistical analysis on the FPAs. The participant's ability to achieve the target FPAs was analyzed through calculation of target achievement rate. This rate is the percentage of good steps the participant have taken. A good step is defined as a step with FPA within ± 3 degrees of the target FPA.

3.0.5 System usability analysis

From the filled in SUS questionnaire, the SUS score was calculated in order to obtain an insightful value. This was done with the following procedure [30]:

1. The score contributions for each item, which can range from 0 to 4, were calculated. Odd-numbered items, which are positive statements, were calculated by subtracting 1 from the circled

number. Meanwhile, even-numbered items were calculated by subtracting the circled number from a value of 5.

2. The score contributions were then added from all of the ten items to get the sum, which is multiplied by 2.5 to get an overall SUS score.

Although a score above 68 is considered above average and anything below is average. As the final SUS score is not a percentage value, scores were compared to a normalized percentile rank [30]. Through the SUS, the perceived usability of the participants was analyzed.

Chapter 4

Results

There was a total amount of 4 subjects (age $= 19.5 \pm 0.5$ years; body mass index $= 19.1 \pm 2.9kg/m^2$). From a random distribution with the specified criteria, the gender of the participants is evenly distributed with two 2 males and two 2 females.

The experiments were first done using lower-body configuration and MVN Studio 4.4.0. This set-up was done with the first two subjects (1 male, 1 female; age $= 20$ years; body mass index $= 19.6$ and $17.9kg/m^2$). As MVN Studio version 4.4.0 compensates for orientation drift based on magnetic measurements, measurements were affected by magnetic interferences from the building environment; thus, the recorded data quickly became distorted over time. This resulted in unreliable results as calculating the correct FPAs required accurate positional data of the feet. The results from this set of experiments can be found in Appendix C.

Table 4.1: *Analysis of all subject's baseline walking*

Subject 1 baseline

	LEFT	**RIGHT**
Step count	58	51
Outlier FPA amount	2	0
Mean FPA	8.8023	-0.4798
Standard deviation	4.8439	5.3402

Subject 2 baseline

	LEFT	**RIGHT**
Step count	75	27
Outlier FPA amount	4	26
Mean FPA	-7.7297	27.3975
Standard deviation	2.9412	0

Subject 3 baseline

	LEFT	**RIGHT**
Step count	95	97
Outlier FPA amount	6	5
Mean FPA	-4.1291	-2.6928
Standard deviation	5.9062	5.2098

Subject 4 baseline

	LEFT	**RIGHT**
Step count	87 (50)*	87
Outlier FPA amount	11	1
Mean FPA	11.4102	-1.6695
Standard deviation	8.618	4.696

*took first 50 steps instead due to distortion in MVN - analysis that follows is also performed with this step count value

The last two subjects (1 male, 1 female; age $= 19$ years; body mass index $= 22.1$ and $17.0kg/m^2$) performed the experiments with full-body configuration and MVN Studio 4.97.1. This newer beta version of MVN Studio allowed for more reliable results, as it is not susceptible to magnetic interferences, unlike version 4.4.0. Version 4.97.1 utilizes an optimization-based method to compensate for orientation drift. The results from this set of experiments can be found in Table 4.2.

The table shows analyzed values of FPA from all the trials in the experimental set. Both subjects recorded approximately the same amount of footsteps. The outliers were counted in all the trials and excluded from analysis, such that only meaningful steps were taken into account. Outliers were defined as anything above absolute 30 degrees.

Among the meaningful steps, in which the first step of each foot was not included, the calculated FPA from each trial were analyzed. The first steps were excluded from meaningful steps as to obtain data that better represents the participants′ gait. Meaningful steps also excluded the duplicated FPAs in the data, which was a result of when the feedback calculation is not updated due to the thresholds not being reached.

With the mean FPA calculated for each trial, comparison can be made with each participant's mean FPA from his or her baseline trial, resulting in the mean FPA deviation from baseline. The mean FPA for all the trials with targets can be found in Table 4.2 and the mean FPA for the baselines of all subjects can be found in Table 4.1. The average standard deviation of all the trials from both subjects is 7.25 degrees. During analysis of the Subject 4's baseline, only the first 50 of the 87 steps taken were used to calculate the mean FPA. This is because around after the 50th step, the subject has accidentally slightly relocated the sensors, which resulted in distorted positional data.

Table 4.2: Results of prototype testing from gait training. *From each trial, the FPA and corresponding values for both feet are shown. The step count logs the amount of times that the foot is considered to be down, with the threshold conditions taken into account. The outlier shows the amount of calculated FPAs that are above 30 degrees (either toe-in or out). Mean FPA is the mean of all the calculated FPAs (not including repetitive updates, which happens when stride length is too small), excluding the first steps. The same applies for standard deviation (Std). The good steps are the count of the subjects steps that fall within 3 degrees from the target FPA and is used to calculate the target achievement rate. As there are some repetitive counts of non-updated FPAs, the amount of repetitive count is used to calculate the true target achievement rate. Apart from this, the mean FPA was compared to the subject's baseline to calculate the mean change from baseline.*

	SUBJECT 3							
	TRIAL 1		**TRIAL 2**		**TRIAL 3**		**TRIAL 4**	
	5° toe in		*0° toe straight*		*10° toe out*		*15° toe out*	
	LEFT	**RIGHT**	**LEFT**	**RIGHT**	**LEFT**	**RIGHT**	**LEFT**	**RIGHT**
Step count	107	125	106	119	100	103	101	109
Outlier FPA amount	16	8	14	7	12	8	34	7
Mean FPA (°)	0.85	-1.06	-1.19	-2.87	-12.95	5.87	-16.74	9.83
Standard deviation (°)	9.70	8.36	7.17	5.72	7.9053	6.51	6.80	5.32
Mean change from baseline (°)	4.98	1.64	2.94	-0.18	-8.82	8.56	-12.61	12.52
Good steps ($\pm 3^\circ$ from target)	15	19	35	53	0	36	0	26
Target achievement	24.30%	28.80%	52.83%	64.71%	52.00%	53.40%	29.70%	34.86%
Repetitive FPA count	4	23	2	16	2	5	3	10
True target achievement	16.48%	16.24%	38.04%	47.32%	0.00%	37.89%	0.00%	25.49%

	SUBJECT 4							
	TRIAL 1		**TRIAL 2**		**TRIAL 3**		**TRIAL 4**	
	5° toe in		*0° toe straight*		*10° toe out*		*15° toe out*	
	LEFT	**RIGHT**	**LEFT**	**RIGHT**	**LEFT**	**RIGHT**	**LEFT**	**RIGHT**
Step count	108	105	103	108	105	104	111	118
Outlier FPA amount	27	17	30	19	13	9	24	19
Mean FPA (°)	11.16	1.81	11.03	0.47	5.96	8.41	-3.57	11.97
Standard deviation (°)	8.23	4.76	8.65	6.55	8.62	7.02	8.67	6.03
Mean change from baseline (°)	-0.25	3.48	-0.38	2.14	-5.45	10.08	-14.98	13.64
Good steps ($\pm 3^\circ$ from target)	2	11	4	35	16	36	2	25
Target achievement	4.63%	22.86%	12.62%	48.15%	5.71%	52.88%	9.01%	33.05%
Repetitive FPA count	15	11	10	15	10	9	6	13
True target achievement	2.47%	12.50%	5.48%	39.33%	17.39%	37.89%	2.30%	25.25%

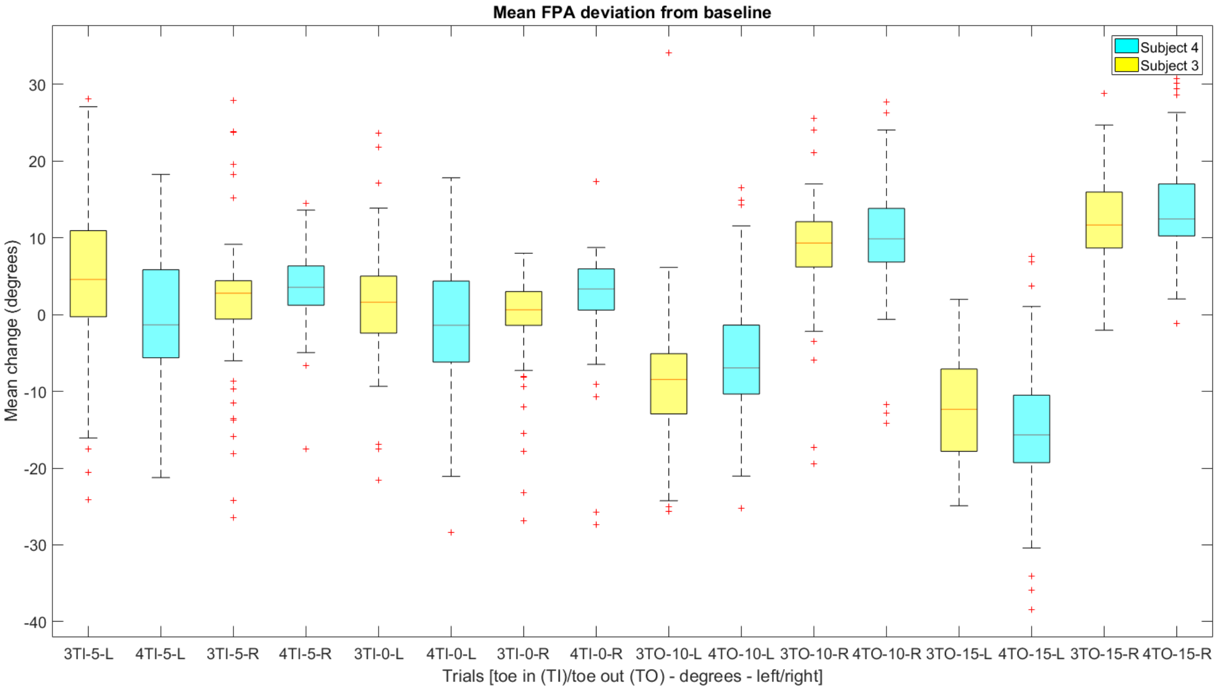

Figure 4.1: Box plot of mean FPA deviation from baseline. *Visualization of the mean change in FPA from baseline for each trial and foot of each subject (not taking into account the first step).*

From the analyzed data, the mean change from the baseline can be visualized for each foot in each trial per subject (see Figure 4.1).

The subjects′ ability to modify their gait can also be visualized through the rate at which they are able to adjust and maintain their FPA to be within 3 degrees of the target angle (see Figure 4.2). Most participants reported that trials 1 and 4 (large toe-in and large toe-out) were more difficult than trials 2 and 3 (slight toe-in and slight toe-out).

With the counts of the calculated steps, outliers, and repeated calculations, analysis was done on the steps of the subjects in all the trials with projected target. This analysis can be seen in Figure 4.3 and provides an overview of how much of the steps made were meaningful. If the steps were not meaningful, the chart also shows how much of those steps are due to outliers and how much due to duplicate values of FPAs. On average, 75.88% of all steps from both subjects were meaningful.

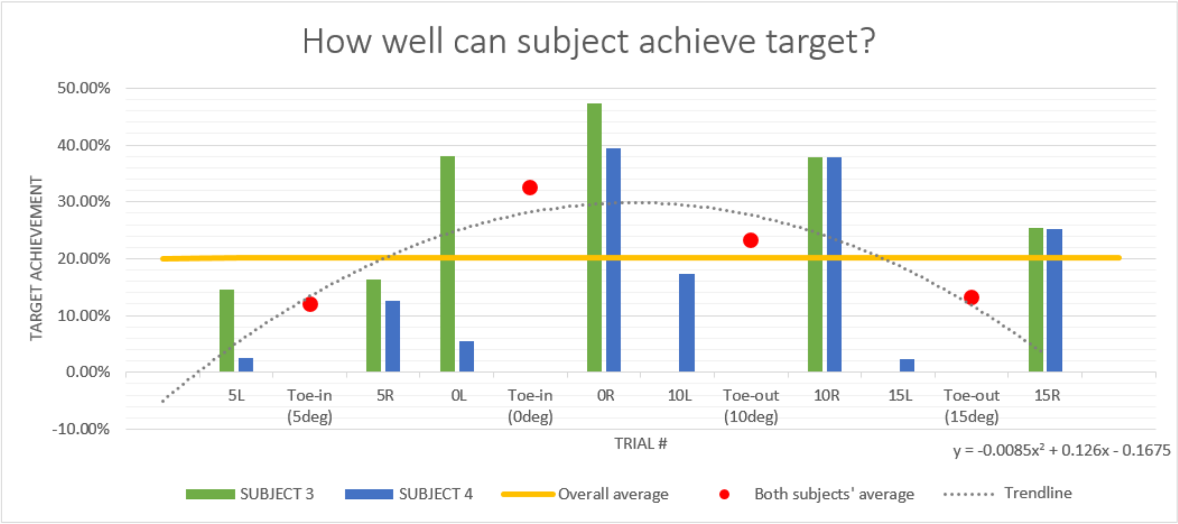

Figure 4.2: Subjects′ Performance Analysis *Each subject's ability to modify gait is visualized by target achievement, taking into account the duplicate updates of FPA (yellow line is the mean target achievement for both subjects at 20.26%). The red dot indicates the average of both feet for both subjects. The trend line indicates the difficulty of each trial, based on subjects′ performance in achieving the target.*

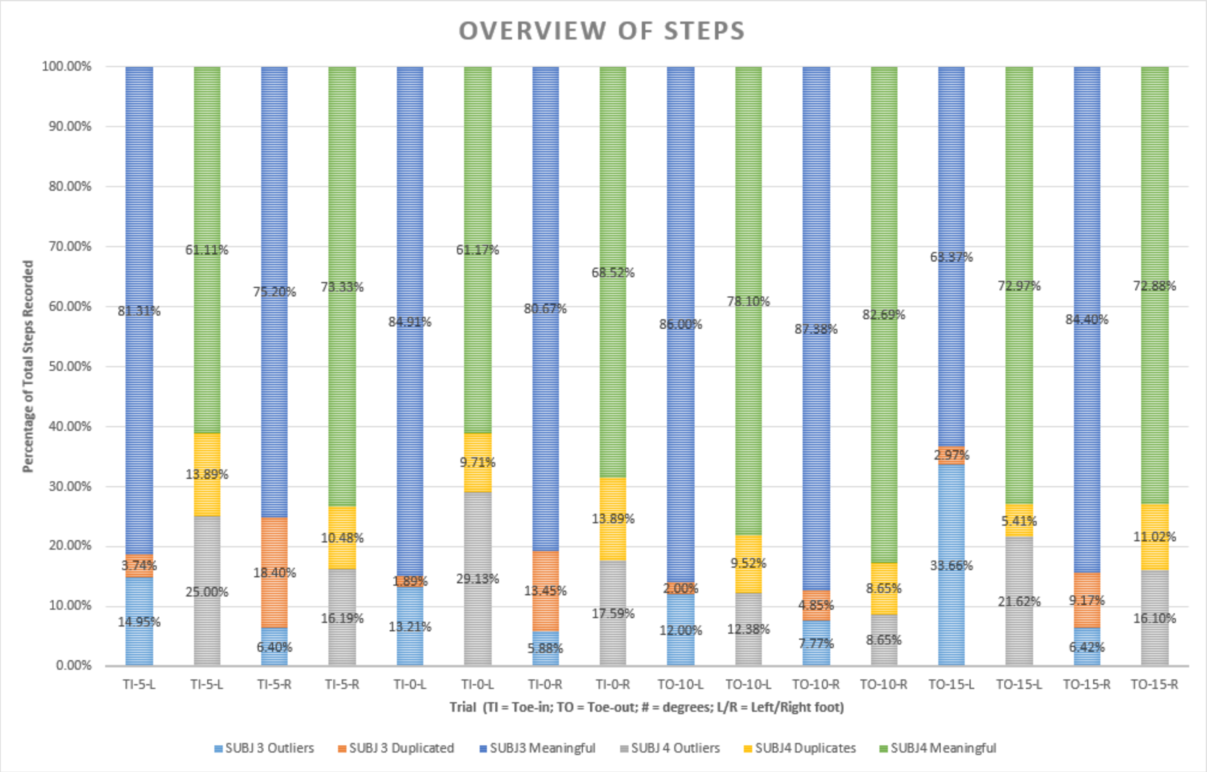

Figure 4.3: Step analysis. *Overview of all steps recorded for all target-projected trials for both subjects, separating between trials and feet. In this case, 'Outliers'refer to calculated FPAs that are larger than absolute 30 degrees, while 'Duplicates'refer to FPA values that were recorded when the feedback has not yet updated.*

As for the SUS scores, as seen in Table 4.3, the first set of experiments resulted in a mean SUS score of 60. While the mean SUS score for the second set of experiments is 75. Once compared to Bangor's normalized adjective rating, the usability for the first set is considered to be "OK", while that of the second set is "good". Bangor's adjective ratings are: "best imaginable", "excellent", "good", "OK", "poor", "awful"and "worst imaginable"[30].

Table 4.3: SUS scores. *Analysis of SUS results from calculation of cumulative scores per question to final SUS score from each subject. SUS score greater than 68 is considered to be above average. Overall mean SUS scores from different sets of data and also shown along with their corresponding adjective ranking.*

Question No.	**Score for Subject**			
	1	**2**	**3**	**4**
1	1	1	2	3
2	4	4	3	3
3	1	4	2	3
4	4	2	3	3
5	3	3	2	4
6	0	1	2	4
7	3	4	3	4
8	1	2	2	4
9	1	1	2	4
10	4	4	3	4
Sum:	22	26	24	36
SUS SCORE:	**55**	**65**	**60**	**90**

	Mean Value		
	Subjects 1 & 2	**Subjects 3 & 4**	**Overall**
SUS Score	60	75	67.5
Adjective ranking	ok/fair	good	good

Chapter 5

Discussion

5.0.1 Thresholds and safety protocols

From the results obtained, it can be clearly seen that the footstep counts for left and right foot of each trial do not always correspond with each other. This is due to the step threshold enforced in the calculation script. If there are not enough samples or if thresholds are not reached on each foot, then step is not counted. These protocols allow for more reliable results in the FPA calculations, making sure that FPA is not calculated from a misstep. Nevertheless, there are still outliers (defined as FPA larger than absolute 30) in the calculated FPAs. Apart from the misstep from the subject, the FPA outliers could be miscalculated FPAs (which happens when stride length is too small) or it could be the steps that were taken to make large turns (such as when reaching the end of the walking path).

When the stride length is too low, the FPA is often miscalculated due to the instability in the calculated walking angle. Even though each subject walks at the same pace throughout the experiment, the calculated stride length can sometimes become too low when there are false positives in the step detection, which would result in calculation and update of the projected FPA feedback. For experiments performed with subjects 3 and 4, additional measures in the conditions for updating the biofeedback was also applied for stride length. These additional measures prevented erroneous feedback from being given when the stride length is below a specified threshold, which was adjusted accordingly to the participant's height.

5.0.2 Calibration and environments

The experiments performed in this study have shown that it is very important for this system to be calibrated well, both from MVN and Unity. This system is very sensitive to orientation changes in the position of the feet. If not calibrated properly, all calculations of FPA will have a certain offset error; thus, the biofeedback provided is not accurate.

A possible source of error in the results is in the drift of the positions of the feet after calibration and in the calibrations itself. It is difficult to assess to what extent the impact of calibration has on the errors, as it is difficult to evaluate the difference in each calibration. Often times everything works properly during the calibration, but once the subjects start moving around, other parameters begin to influence the result. In order to correct for positional drift, step contact updates (velocity and height updates) were applied to the feet. These updates may impose a slightly different segment orientation compared to the actual pose.

In MVN Studio version 4.4.0, errors in tracking will appear from magnetic interferences, given the fact that the magnetic field may differ considerably across a large indoor hall. Particularly, the feet will be among the segments which will be disturbed the most due to their direct contact with the floor. Xsens MVN Studio 4.97.1 does not make use of magnetometers apart from the N-pose to define the magnetic north. However, joint constraints are utilized in an optimization approach to correct for the drift between the body segments. Since this is a beta version its performance is still unknown, especially for real-time applications.

Avoiding magnetic interference by performing the experiment outdoors has also been attempted, but different problems have to be dealt with in regards to the Microsoft HoloLens augmented reality glasses. The HoloLens often relies on walls to render the environment for mapping its position. Due to the minimal amount of walls, the HoloLens is often trying to map the environment, resulting in glitches in the visualization system.

Even though the FPA values analyzed in the study excluded the first and second step, the degree of impact of this exclusion on the results is very low that it is insignificant. This is because everything is averaged and the differences between mean FPA values with and without the first steps are very small (difference of around a tenth of a degree).

5.0.3 System accuracies

Once thresholds for step detection are adjusted accordingly to subject's height, the system is quite accurate at detecting when the foot is down. The average position of the foot taken when foot is down is just slightly after mid-stance phase, which is when foot is flat on the ground.

Calibrations of the system were more or less accurate. Observations were written down for how participants walked and these observations often times match the calibrated estimated kinematics (which was shown on a body-segments model). For example, it was observed that Subject 4 often walked with left toe slightly inverted and this could clearly be seen in the mean FPAs for the baseline (Table 4.1). Most of the mean FPAs of the right and left foot are often also opposite in signs, which is representative of the natural orientations of the human feet.

If calibration is done well, the system is also accurate at calculating foot angle. As for walk angle, there are some inconsistencies due to the atan2 function used in the Unity script to calculate the walk angle. With this function, the orientation of the walk vector is often inverted for smaller vectors (for example, instead of 350 degrees, the function outputs 10 outputs). This is the main reason for why miscalculations occurred for shorter stride lengths.

Because of the instabilities, the system is currently not accurate enough. If the device is to be used in application for KOA patients, it is important that the system is stable and outputs true positives. Otherwise, it could put the health of the patients at risk.

5.0.4 Performance analysis

In Figure 4.1 progression of mean FPA deviation can be clearly seen, especially in the later trials of toe-out. For larger values of target angles, there were larger FPA deviations from the baseline. A reason for why it is seen clearer in toe-out trials than toe-in trials is because the average human foot progression angle is around 3 to 5 degrees, which means that the difference between this and the toe-out targets are most likely larger than between the toe-in targets.

It should also be noted that from one trial to another, the mean FPA deviates towards the provided target angle. Thus, the system can be considered usable for gait modification. Although, this would only be true if the calibrations are done properly.

5.0.5 System usability

For this system, the usability score is considered satisfactory for first-round prototype testing. From the preliminary prototype testing and the actual first-round testing, the improvement is already reflected in the change in the mean SUS scores from the first set of experiments (60) to the second set of experiments (75). The reason for why the SUS score for the second subject is higher despite being in the first set of experiments, in which improvements have not yet been applied, could be because Subject 2 was tall and had a larger stride length than Subject 1. This larger stride length resulted in less miscalculated steps. As of now, the system seems to work better with taller participants with longer stride lengths. This evidence may imply that stride length is more important for system accuracy than calibration.

5.0.6 Effectiveness for gait modification

Even though results show that this system is usable and can be used for performing gait modification, it is still not as effective as the current technologies for gait modification. No matter which Xsens MVN Studio version is used, IMU orientation will always eventually drift; either due to magnetic field (such as in MVN Studio 4.4.0) or joint constraint modeling errors (in version 4.97). As for mid-stance step detections, it is much simpler and more accurate when done on an instrumented treadmill than through IMU measurements, especially real-time. The laboratory treadmills are able to do these measurements through the use of force plates. Nevertheless, IMUs have more potential than treadmills for creating an ambulatory system.

Chapter 6

Conclusion

A system composed of IMU sensors and augmented reality glasses allow for an ambulatory system that is feasible for gait analysis, although usability could be improved. With improved usability, the system should also become more effective for gait training. As of now, the results may show that the system is usable and can be used for gait modifications, but no strong claims can be drawn from this study, especially with reliable dataset from only two subjects. Despite the instability currently in the system, there is potential in this technological setup, although further development and research is required. With this ambulatory system, gait training interventions will be more clinically available and easily accessible and can be employed to aid in preventing or slowing down the progression of diseases like knee osteoarthritis.

6.0.1 Recommendations

There are multiple recommendations for improvement of this system or for research in this field of technology.

To further improve the effectiveness of this system, further developments can be done to improve the accuracy for small steps. This was a problem that contributed a lot to the system's instability. If this problem can be solved, the accuracy of this system will be improved; thus, the reliability of the system will also improve. It would also be interesting to investigate the correlation between walking speed/stride length and the accuracy of the system.

Future developments should also aim to build the program from Unity into an application, such that it can be easily opened directly on the HoloLens. The current challenge with building this system into a Windows Store application is due to the incompatibility of the Xsens MVN Live Animation Plugin for building into a virtual/augmented-reality application. During the course of this experiment, the biofeedback was projected from Unity as a holographic emulation. Further developments for the application could be the addition of audio feedback.

The design of the visual feedback could also be further explored. During the development phase, it was also considered to exaggerate the projected feedback, such that smaller changes in foot angle can be quickly noticed. This was never applied to the design of the visualization as the system has not yet been stable enough to project small changes in angles. Research can also be done to optimize the feedback rate. Further research can be done to investigate the optimal percentage of target achievement a subject should achieve for the best gait modification intervention.

As stated earlier, the aspect of color ranges for additional feedback in the visualization was also attempted for the design of this system. Unfortunately, the color ranges did not work well enough for any observations to be drawn from it. Thus, further improvements could be done on the dynamic color ranges of the feedback arrows to test its effectiveness in aiding visual biofeedback.

As this study was performed with the use of healthy participants, the results may not be as representable as it would be if performed with actual patients of KOA. After further improvements have been made on the development of the system, further research can be performed with actual KOA patients, using gait modification interventions with a longer time span.

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Appendices

Appendix A

Experimental protocol

Subjects

A minimum of four and a maximum of ten volunteers will be recruited from the students and staff of the University of Twente. The participants will be free of recent musculoskeletal or neuromuscular disorders.

Exclusion Criterion: People who require use of eyeglasses while walking.

Instrumentation

Augmented Reality Glass Microsoft HoloLens
The Microsoft HoloLens, a mixed reality glass will be used to visualize the biofeedback provided by Xsens MVN input (real-time tracking) and pre-defined values (target).

Inertial Motion Capture Suit - Xsens MVN Awinda
The lower body configuration of the Xsens MVN suit will be used. This contains 7 inertial measurement units (IMUs) placed in the following body segments: pelvis, thighs, shanks, feet. The system can estimate kinematics of the body segments in an ambulatory environment.

System Usability Scale (SUS)
The System Usability Scale (SUS) is an evaluation tool in the form of a questionnaire. This standard questionnaire will be given for the subject to fill in after having performed the experiment.

Set-up

Each subject will perform the experiment indoor along the corridor in Zuidhorst building of the University of Twente (going from Meander to NanoLab). Measurements may be affected by magnetic interference in indoor environments, so calibration may have to be done often. Each subject will have to walk around 70 meters along the corridor and back (around 140 meters altogether) for each trial.

Experimental Procedures (*Total: 62 minutes*)

The procedures in this section can be followed once the subject has read the information brochure of the research and has signed an informed consent form.

Step 1 - Body measurements (10 minutes)

1. Measure the following body dimensions with a conventional measuring tape:
    - Height (distance from top of head to ground with subject standing upright),
    - Pelvis width (distance between the anterior superior iliac spines),
    - Hip height (distance from the greater trochanter to the ground),
    - Knee height (distance of the lateral tibial epicondyle from the ground),
    - Ankle height (distance from the lateral malleolus to the ground), and
    - Foot length (distance between the calcaneus and the tip of the hallux big toe).
    - Shoe sole thickness (average thickness of sole of subjects shoes distance from floor to bottom of foot this adds offset to ankle height)
2. Input measured dimensions into MVN Studio.

Step 2 - Placement of hardware (10 minutes)

1. The seven IMUs will be placed in the following locations over the clothing of the subjects using Velcro straps included in Xsens MVN Awinda suit [19]:
    - Pelvis IMU: on posterior side of the pelvis approximately on the L5/S1 joint;
    - Thigh IMU: on the lateral side of the thigh approximately on the middle point between hip and knee joint;
    - Shank IMU: on the anterior/medial side of the shank 5-10 cm below the knee joint (medial surface of tibia); and
    - Foot IMU: Middle of bridge of foot.

    If full-body suit configuration is to be used, add ten more IMUs [19]:

    - Sternum IMU: on middle of chest;
    - Shoulder IMU: on scapula;
    - Head IMU: anywhere on head in headband;
    - Upper arm IMU: on lateral side above elbow;
    - Wrist IMU: on lateral flat side of wrist; and
    - Hand IMU: on backside of hand.

Step 3 - Calibration of Xsens MVN (5 minutes)

1. The subjects stand still in an upright standing pose also known as the N-Pose (see Figure A.1). From the *MVN User Manual*, the N-Pose means the following statements should be observed:
    - Upright stance on horizontal surface;
    - Feet parallel and one foot width apart;
    - Back straight;
    - Shoulders above hips but not pulled up;
    - Arm straight beside body with thumbs forwards. To check, arms should be able to flex and extend at elbow, allowing for movements in the sagittal plane where palms face each other; and
    - Face forward.
2. The placement of the feet will be guided by a custom-made calibration board based on the body dimensions of each subject.

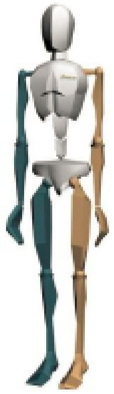


Figure A.1: *Example of N-Pose. Note: Reprinted from MVN User Manual (p. 47), by Xsens Technologies B.V. 2015. Enschede, Netherlands: Author. Copyright 2015 by Xsens Technologies B.V.*

Step 4 - Placement of the Microsoft HoloLens (5 minutes)

1. The subjects will wear the Microsoft HoloLens without wearing any eyeglasses.
2. The visual application designed in the Unity environment will be initialized.
3. The subjects will be asked if they can see clearly specific test objects (geometric objects).
4. At the same time the experiment instructor will have access to the subjects viewpoint on a computer screen which will also be recorded for further post-analysis.

Step 5 - Linking Xsens MVN system with Microsoft HoloLens system (5 minutes)

1. The Unity Plug-In feature of Xsens MVN will be used to stream the captured kinematics in real-time from the device running Xsens MVN Studio to the Microsoft HoloLens.

Step 6 - Calibration of Unity systems (2 minutes)

1. Prior to starting the biofeedback visualization, make sure that subject stands in N-Pose. Once the Play on Unity has been clicked, wait for 15 seconds for the position in Unity to calibrate.

Step 7 - Begin experiment (20 minutes)

1. The subject will initially walk in a comfortable self-selected speed without the use of any feedback (*baseline*) towards the end of the corridor and back. As set-up, the subject will have a walking distance of 75 meters along a straight corridor. If subject reaches end of limited path, subject can turn around and walk back down the same path until the other end is reached.

2. Subsequently, the feedback application will be activated and subject will receive the visual feedback as in Figure A.2.

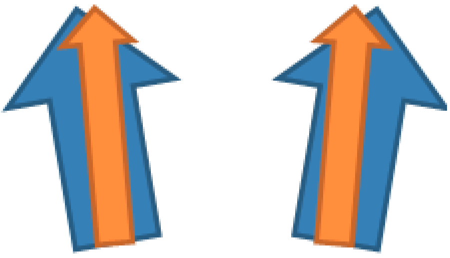


Figure A.2: *Example of the visual feedback interface, where blue arrow is the targeted feedback that subject has to try to reach and maintain. Orange arrow is the average foot progression angle (FPA) across the mid-stance phase of the previous gait cycle for each foot, as estimated from Xsens MVN Studio input.*

3. The first feedback (*trial 1*) should provide a large toe-in target FPA of negative five (-5) degrees, meaning toes should be pointing in a direction parallel to the direction that the subject is facing. The reference directions can be visualized in Figure A.3.

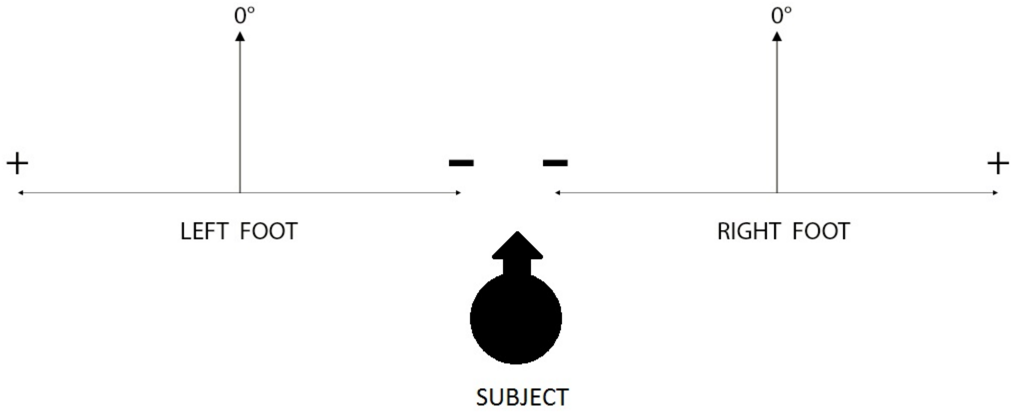


Figure A.3: *Reference directions for toe-in/out angles for subject facing in direction of 0 degrees.*

4. Subject walks to the end of the corridor and back at a comfortable self-selected pace. If end of path is reached, subject turns around and walks towards the other end of the path again until the time is completed.

5. Repeat number 3 and 4 (of step 7) with the following feedback applied for number 4: large toe-in target FPA of negative five (-5) degrees, slight toe-out in target FPA of ten (10) degrees, and large toe-out target FPA of fifteen (15) degrees. Full overview can be seen in Table A.1.

Table A.1: *Trial progression of gait training intervention*

Trial	Target FPA	Target FPA Angle	Distance
Baseline	none	-	2×70 m
1	Large toe-in	$-5°$	2×70 m
2	Slight toe-in	$0°$	2×70 m
3	Slight toe-out	$10°$	2×70 m
4	Large toe-out	$15°$	2×70 m
Washout	none	-	70 m

Step 8 - System Usability Scale (SUS) Questionnaire (5 minutes)

1. 1. Have the subject fill out the SUS questionnaire.

Data collection and storage

The following data will be measured and collected:

- Lower body segment dimensions

  This data is inputted into system of MVN studio for proper calibration of the Xsens MVN Awinda inertial motion capture suit and used for calculations.

- Lower limb segment kinematics

  This is the data that is used to drive the biofeedback.

- Adaptation to instructed gait pattern

  This is used for analysis.

- Perceived usability of system

  This subjective data is collected with the SUS.

- Demographics: gender, age, height, and weight of subject

  Although not important for the primary goal of the research, this data could still be useful during analysis of results, as these demographics are biometrics that can affect a persons gait.

- Field of view of the subject during the experiment

  The view that the subject perceives through the Microsoft HoloLens will be recorded and could possibly be used for reference during analysis of results.

Collected data is to be stored on researchers device during duration of experiments and analysis. Following the completion of research project, collected data will be transferred to storage device belonging to Biomedical Signals & Systems (BSS) research group and removed from researchers device.

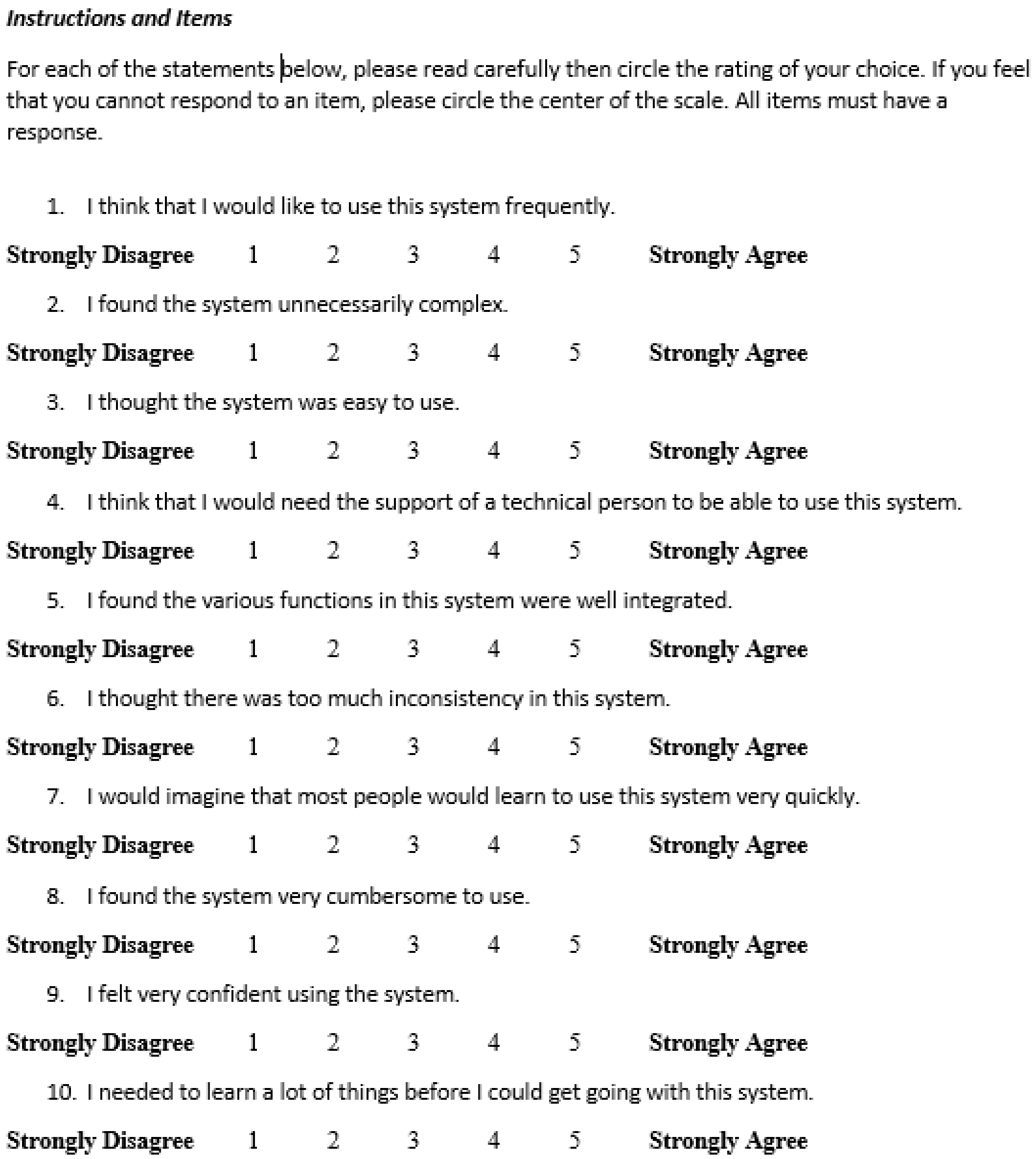
The anonymity of subjects will be ensured by assigning ID numbers in the database. Information brochure and informed consents are also given prior to start of experiment.

Informed consent forms will be stored in non-digital format in a location other than the collected data.

Appendix B

System Usability Scale (SUS)

Below is an example of the standard questionnaire given to participants after completion of gait analysis experiment [29].



Instructions and Items

For each of the statements below, please read carefully then circle the rating of your choice. If you feel that you cannot respond to an item, please circle the center of the scale. All items must have a response.

1. I think that I would like to use this system frequently.

Strongly Disagree 1 2 3 4 5 **Strongly Agree**

2. I found the system unnecessarily complex.

Strongly Disagree 1 2 3 4 5 **Strongly Agree**

3. I thought the system was easy to use.

Strongly Disagree 1 2 3 4 5 **Strongly Agree**

4. I think that I would need the support of a technical person to be able to use this system.

Strongly Disagree 1 2 3 4 5 **Strongly Agree**

5. I found the various functions in this system were well integrated.

Strongly Disagree 1 2 3 4 5 **Strongly Agree**

6. I thought there was too much inconsistency in this system.

Strongly Disagree 1 2 3 4 5 **Strongly Agree**

7. I would imagine that most people would learn to use this system very quickly.

Strongly Disagree 1 2 3 4 5 **Strongly Agree**

8. I found the system very cumbersome to use.

Strongly Disagree 1 2 3 4 5 **Strongly Agree**

9. I felt very confident using the system.

Strongly Disagree 1 2 3 4 5 **Strongly Agree**

10. I needed to learn a lot of things before I could get going with this system.

Strongly Disagree 1 2 3 4 5 **Strongly Agree**

Appendix C

Results from first set of experiments

Table C.1: *Calculation of SUS scores for each subject, along with mean scores and adjective ranking.*

	SUBJECT 1							
	TRIAL 1		**TRIAL 2**		**TRIAL 3**		**TRIAL 4**	
	5° toe in		*0° toe straight*		*10° toe out*		*15° toe out*	
	LEFT	**RIGHT**	**LEFT**	**RIGHT**	**LEFT**	**RIGHT**	**LEFT**	**RIGHT**
Step count	70	74	56	57	58	59	57	61
Outlier FPA amount	26	19	23	15	20	14	12	16
Mean FPA (°)	9.3321	2.0024	11.7898	4.2168	8.268	9.9473	-1.2823	13.4173
Standard deviation (°)	12.0815	7.5771	12.1053	7.8582	12.347	9.4481	9.4116	9.1631
Mean change from baseline (°)	0.5298	2.4822	2.9875	4.6966	-0.5343	10.4271	-10.0846	13.8971
Good steps ($\pm 3^\circ$ from target)	9	17	4	24	8	24	7	24
Target achievement	12.86%	22.97%	7.14%	42.11%	13.79%	40.68%	12.28%	39.34%

Table C.2: *Calculation of SUS scores for each subject, along with mean scores and adjective ranking.*

	SUBJECT 2							
	TRIAL 1		**TRIAL 2**		**TRIAL 3**		**TRIAL 4**	
	5° toe in		*0° toe straight*		*10° toe out*		*15° toe out*	
	LEFT	**RIGHT**	**LEFT**	**RIGHT**	**LEFT**	**RIGHT**	**LEFT**	**RIGHT**
Step count	109	104	99	102	99	101	95	100
Outlier FPA amount	17	47	34	38	32	46	32	42
Mean FPA (°)	3.4415	12.8144	0.6522	17.1877	-0.8934	17.917	1.942	21.7925
Standard deviation (°)	11.1972	10.7496	10.1455	6.9164	9.6358	7.2109	10.9886	6.6626
Mean change from baseline (°)	11.1712	-14.5831	8.3819	-10.2098	6.8363	-9.4805	9.6717	-5.605
Good steps (±3° from target)	30	3	32	4	17	14	3	13
Target achievement	27.52%	2.88%	32.32%	3.92%	17.17%	13.86%	3.16%	13.00%

	TRIAL 1.2		**TRIAL 2.2**	
	5° toe in		*0° toe straight*	
	LEFT	**RIGHT**	**LEFT**	**RIGHT**
Step count	99	102	99	102
Outlier FPA amount	34	38	34	38
Mean FPA (°)	1.36	7.6992	0.7851	4.6123
Standard deviation (°)	9.1153	11.1276	13.2687	10.1887
Mean change from baseline (°)	9.0897	-19.6983	8.5148	-22.7852
Good steps (±3° from target)	36	9	9	21
Target achievement	36.36%	8.82%	9.09%	20.59%