EVALUATION OF MEASUREMENT METHODS FOR DETERMINING INDIVIDUAL MOVEMENT IN CROWDS

Gabriel Larsson & Jesper Friholm
| Division of Fire Safety Engineering | LTH | LUNDS UNIVERSITET

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Gabriel Larsson
Jesper Friholm

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Utvärdering av mätmetoder som används för att fastställa hur personer förflyttar sig i folkmassor

Authors
Gabriel Larsson and Jesper Friholm

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Abstract
Since the mid-20th century, investigations of parameters that affect crowd movement have mainly been performed via video analysis. However, modern alternatives have been used to investigate how a person moves, but only with one person at a time. The purpose of this study is to utilise two different measurement methods in order to collect material that can be investigated in the future, both during this thesis and further on, and to evaluate the methods used. The evaluation is performed in order to establish which method is preferable in future studies. Eye tracking equipment will be combined with one of the methods to review what people look at when moving in a crowd. To do this, two experiments were carried out, one utilising the traditional video capture method and the other using a motion capture system. The results show a possible logarithmic relationship between inter person distance and step length, in relation to velocity. A relationship between contact distance and velocity is dubbed "contact buffer", and seems to be approaching 0.3 s. After evaluating the two methods used, the optical capture method is deemed the more favourable, although there are advantages and disadvantages for both. The eye tracking results point at a possible dependence between what a person looks at, and both the occupant density and the height of the person.

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Brandteknik
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

www.brand.lth.se
Telefon: 046 - 222 73 60

Division of Fire Safety Engineering
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

www.brand.lth.se
Telephone: +46 46 222 73 60

Preface

The following report is a Bachelor of Science thesis from the Fire Protection Engineering program at Lund University, Sweden. It is a part of an ongoing project called "Crowd Safety: Prototyping for the Future" which is financed by Brandforsk (reference number 200-161). Without their funding, this thesis would not have been possible to carry out and great thanks is therefore directed towards Brandforsk for making this study possible. Our prospect is that further research can be built upon it to improve and increase the knowledge of crowd movement.

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Summary

When establishing if a building is safe from a life safety perspective, current design guidance documents use a basic flow rate from a single uniform population which remains unchanged since the regulation of passageway and door sizes during the mid-20th century. The demographic changes that have occurred since then could mean that the current build up environment poses an unquantified risk regarding life safety. The investigations performed in order to quantify parameters relating to the movement of crowds have mostly been done by recording a flow of people using video cameras and then utilising a video analysis software. However, technological advancements over the last 70 years have produced alternatives that could possibly replace the older methods. In order to determine if there is a viable alternative approach, an investigation is needed.

As a part of this investigation, two experiments were conducted, where one utilised video cameras and the other a motion capture system. During the video capture experiment, 59 people participated in different tests were the occupant density was varied. This experiment was also combined with eye tracking technology to investigate what people look at when moving in a crowd. This experiment was performed at Lund University in Lund, Sweden. During the motion capture experiment, four people participated in each test and the experiment was held at University College Dublin in Dublin, Ireland.

The results from the two measurement methods regarding inter person distance, step and stride length, and contact distance are presented in two different ways. One is an absolute distance graph and the other is a relative distance graph, which has not been presented in this way before. The results from the eye tracker are presented with focus on how the users gaze pattern is affected by a variation of occupant density and the height relationship between the user and the person ahead.

A relationship between inter person distance and step length, in relation to velocity was found to be linear. However, additional data points could prove this relationship to be logarithmic. The interaction between the heels of one person and the toes of the person behind, or the contact distance, shows indication of having a linear relationship in relation to velocity. From this relationship the contact distance can be converted into a time, giving a value that approaches 0.3 s which is dubbed “contact buffer”.

During a comparison of two tests with similar velocity, one from the video capture experiment and one from the motion capture experiment, it was found that the average inter person distance was the same. This could potentially mean that the results from tests with fewer participants are applicable to larger crowds. There are advantages and disadvantages with both measurement methods. The motion capture method produces results with higher resolution at a much faster rate compared to the video capture method, but the hardware and software are expensive. The video capture method is user friendly and economically cheaper, however it has a user dependant accuracy and can be time consuming. In the end, the motion capture method seems to be more favourable.

The eye tracking results show an indication that what a person looks at while moving through a crowd depends on both the current occupant density and the height of the person that is using the eye tracking equipment.

Sammanfattning

När man fastställer om en byggnad är säker ur ett livsäkerhetsperspektiv, används riktlinjer som utnyttjar en grundläggande flödeshastighet från en enhetlig befolkning som har varit oförändrad sedan regleringen av passage och dörrstorlekar som skedde under mitten av 1900-talet. De demografiska förändringarna som skett sedan dess kan innebära att den nuvarande infrastrukturen utgör en icke kvantifierad risk för människors säkerhet. Forskare har generellt använt sig av videokameror för att undersöka parametrar som påverkar hur grupper av människor rör sig, men teknologiska framsteg under de senaste 70 åren har levererat alternativ som skulle kunna ersätta de äldre metoderna. För att avgöra om det finns ett praktiskt alternativ så krävs det en undersökning.

Som en del av den här undersökningen utfördes två olika experiment där två olika metoder för att samla in data användes. I ett av dem användes videokameror och i det andra användes ett motion capture system, som kan följa en persons rörelser. Under experimentet med videokameror deltog 59 personer under olika försök där antalet personer varierades. Det här experimentet kombinerades även med eye tracking utrustning, som följer en persons blick, för att undersöka vad folk tittar på när de rör sig i en folkmassa. Experimentet utfördes på Lunds Universitet i Lund, Sverige. Under experimentet med motion capture systemet deltog fyra personer under varje försök och experimentet hölls på University College Dublin i Dublin, Irland.

Resultaten från de två metoderna relaterat till inter person distance, step och stride length, och contact distance presenteras på två olika sätt. Det ena sättet är en graf som visar det absoluta avståndet och det andra är en graf som visar det relativa avståndet, vilka inte har presenterats på det här sättet förut. Resultatet från eye trackern presenteras med fokus på hur befolkningstätheten och längdförhållandet till personen framför påverkar användarens blickmönster.

Ett linjärt förhållande mellan inter person distance och step length, i relation till hastighet hittades. Detta förhållande kan visa sig vara logaritmiskt vid en mer omfattande undersökning. Samspelet mellan hälarna på en person och tårna på en person som går bakom, eller contact distance, visar en indikation på ett linjärt förhållande i relation till hastigheten. Contact distance kan omvandlas till en tid, vilket ger ett värde som närmar sig 0.3 s, detta myntas som ”contact buffer”.

Under en jämförelse mellan två försök med snarlika hastigheter, ett från experimentet med videokameror och ett från experimentet med motion capture systemet, visade det sig att medelvärdet för inter person distance var samma i båda försöken. Detta kan potentiellt innebära att resultat från experiment med färre deltagare kan vara applicerbara på större folkmassor. Det finns fördelar och nackdelar med båda metoderna. Motion capture metoden ger resultat med en hög upplösning på kort tid jämfört med video capture metoden, men hård- och mjukvaran är dyr. Video capture metoden är användarvänlig och billigare, sett ur en ekonomisk synpunkt, men noggrannheten är användarberoende och metoden kan vara tidskrävande. I slutändan verkar det som att motion capture metoden är mest gynnsam.

Eye tracking resultaten visar en indikation på att vad en person tittar på vid förflyttning i en folkmassa beror både på befolkningstätheten samt personens längd.

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1 Introduction

To establish if a building or transportation system is safe from a life safety perspective, calculations regarding evacuation time are carried out, often with simple flow rates and walking speeds. Unfortunately, current design guidance documents typically use a basic flow rate from a single uniform population, which remains unchanged since the regulation of passageway and door sizes during the middle of the 20th century. Considering that the reliability of these has been questioned, they are now regarded as out of date (Thompson, Nilsson, Boyce, & McGrath, 2015). Because of this, these data sets potentially pose an unquantified risk to life safety which is the very thing that they are used to determine. The authors of what are widely considered as the most significant data sets in North America (Fruin, 1971) and (Pauls, 1996) have asked for the removal of their data sets from future design guides with the notion that they no longer are applicable.

There is an ongoing project called "Crowd Safety: Prototyping for the Future" funded by Brandforsk (Reference number 200-161) investigating the way that people essentially slow each other down in crowds. As a part of this, a literature study of which parameters affect crowd movement was performed by Andreas Hansen, namely "A scoping review for the parameters of crowd movement" (Hansen, 2018). In this report, Hansen lists 22 parameters that have an impact on, and are of importance to, crowd movement. The parameters are:

- Age
- Step frequency
- Height
- Fitness
- Culture
- Weight
- Social relations
- Occupant density
- Emotional state
- Body projection area
- Bottlenecks, openings
- Lateral sway
- Gender
- Headway/inter person distance
- Emergency or non-emergency
- Health status
- Fatigue
- Step size
- Vision
- Personal space
- Group size
- Stair gradient

It could be argued that these should be called factors instead of parameters, the difference being that a parameter is defined as an arbitrary constant whose value characterises a member of a system (Merriam-Webster, Accessed 2019), while a factor is a circumstance, fact or, influence that contributes to a result (Oxford University Press, Accessed 2019). However, since this thesis is part of the same project as the literature study performed by Andreas Hansen, they will be referred to as parameters in order to have consistency within the project. The impact that the parameters have are either direct or indirect, e.g. step size has a direct impact while health status has an indirect impact. To investigate how these parameters correlate to crowd movement, a traditional approach would be to do an experiment and perform a video analysis of the collected data. However, this can be very time consuming and it is not always possible due to the fact that a person can be obscured by others which is why that method not might be considered practical at all times. Technological advances have presented alternatives where one is in the form of motion capture systems. Vision is a parameter that would be hard to investigate with either of these methods alone. However, when combined with eye tracking equipment a correlation could possibly be found. The eye tracking technology also enables the consideration of the decision-making that occurs when a person is moving through a crowd and how this decision-making varies depending on the person that is using the eye tracking equipment, and the surrounding variations such as occupant density.

Early experiments were conducted with the help of a simple stop-watch equipment to investigate the relationships between speed-density and flow-density (Hankin & Wright, 1958). However, both the video capture and motion capture methods have been used to investigate pedestrian movement, e.g. (Cao et al., 2016) used video cameras to determine that age composition affects the risk of jams in pedestrian traffic, and (Jelić, Appert-Rolland, Lemercier, & Pettré, 2012) used a motion capture system to establish that step length is proportional to velocity and to investigate body sway. However, the advantages and disadvantages of the methods have not been investigated. Establishing these would aid researchers in choosing the method most suited for their investigation.

The inter person distance, which is often explained by the relationship between velocity and distances (Thompson, 1994), is a major factor that affects the walking speed and the flow rate of pedestrians. It has also been shown that age and increasing of obesity rate has an effect on walking speed and occupant flow rate as well (Cao et al., 2016) (Thompson, Nilsson, Boyce, & McGrath, 2015) (Spearpoint & MacLennan, 2012), which is important to acknowledge considering that the 'elderly' proportion in adult society is predicted to increase in the future (Thompson, Nilsson, Boyce, & McGrath, 2015). More elderly people in combination with a different way of living than in the mid-20th century can have a great influence on the movement patterns and walking speeds in a crowd.

1.1 Scope and Objectives

In this report two methods of measuring crowd movement will be evaluated. The methods are a traditional video capture method, and a more modern motion capture method. The report will focus on comparing values gathered for inter person distance, step length and contact distance, while also comparing the two methods with one another. The video capture will be combined with eye tracking equipment, which will be analysed as well.

The goal of the ongoing project is to ultimately improve the assumptions in evacuation simulators, making the results from these more accurately depict real-life situations. Therefore, the aims of the thesis are as follows

- Establish if these measurement methods can be used to investigate some important parameters, identified in the literature review, that affect the movement in crowds and if one method is more favourable than the other when doing so
- Evaluate if the combination of participants, regarding their height, and the crowd density affect what people look at when moving through a crowd
- Evaluate the usability of the different hardware and software used during the experiments and analysis
- Collect data that can be analysed further in the future

1.2 Method

In this section the process of writing this thesis is presented, which is illustrated in Figure 1.

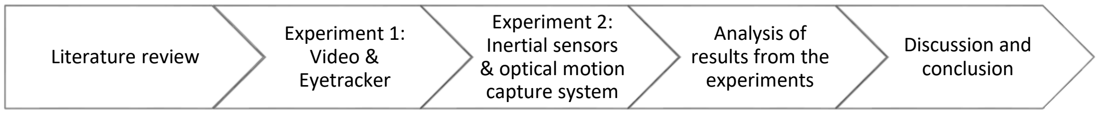

Figure 1 - The work process of the thesis

The work with the thesis started with a literature review of what has been done before in the area of crowd movement, focusing on which experimental methods have been used.

Following this, two major experiments was conducted to collect data for the upcoming analysis. The experiment in which data were collected for the video analysis was performed at the Faculty of Engineering (LTH) at Lund University in Lund, Sweden, while the experiment in which data was collected with a motion capture system was conducted at University College Dublin (UCD) in Dublin, Ireland. The experiment in Lund was combined with eye tracking technology and the experiment in Dublin was combined with inertial sensor technology.

After the experiments, tests were chosen for further analysis. The analysis was followed by a presentation of results and subsequent discussion and conclusion.

1.3 Delimitations

Data was collected during the experiments, but due to a limited timeframe only a fraction was analysed. The rest is sorted and prepared for future research, the implications being:

- The scenarios for the experiments were limited to single file and double file tests
- The populations of the two experiments were mainly students or healthy adults
- Two tests were chosen from the Lund experiment, with two people in each test being analysed regarding their movement.
- The data from the inertial sensors will not be analysed
- The larger project that this thesis is a part of is called "…prototyping for the future…" which means that it is not intended to analyse all data collected in the experiments and quantifying the data exhaustively. Instead the intension is to investigate the basics approaches and to see what can successfully be used for further investigation.

2 Previous research regarding crowd movement

Much research regarding human gait and movement of people has been conducted in the past and the experimental studies have been performed with different measurement methods. However, a majority studies analysed in the literature review part of this thesis have been conducted with image processing, or video analysis. In this chapter, a selection of what have been done in the past is presented.

2.1 Early research

Before the video camera became frequently used, a method of collecting data using observers with simple stopwatches was used. Hankin & Wright (1958) performed studies in subways. The focus was to collect data to find relationships between speed and density, and flow and density in crowds (Hankin & Wright, 1958). Predtchenskiĭ & Milinskii (1978) compiled data from different studies in Russian buildings regarding the same relationships as Hankin & Wright (1958), also with the stopwatch method (Predtechenskiĭ & Milinskii, 1978). There are a few limitations of this method. The location of the observer, in relation to the tracked persons, might have an effect on the collected data, as an observer standing at a different location might press the stopwatch at a different time. This also means that there is a user dependency on the results.

One of the first in-depth analyses of crowd transit was conducted by Fruin (1971). In that study, time lapse photography was used to quantify movement parameters. Time lapse photography means that pictures are taken at regular intervals. The focus was on density at different speeds as well as the relationship between the density and the flow (Fruin, 1971).

In these investigations, the crowd was considered a group of people moving at a uniform flow, instead of treating the crowd as a group of individuals with different characteristics. One reason for this was the lack of computational power required to perform that kind of extensive movement analysis (Thompson, 1994).

2.2 Research using video capture methods

Video capture analysis, with the use of one or more video cameras, has often been used in this field. Several of the experiments were conducted by filming from above, where the participants had reflective markers on them that can be easily detected during the analysis. The analysis can be done either manually frame by frame or automatically by the image processer, if this is an option. Video capture analysis is the only option if a 2D analysis is to be done (Best & Begg, 2006).

The relationship between inter person distance and walking velocity was investigated for the first time by Thompson (1994). He did experiments in Edinburgh where people left and entered buildings. It was recorded with video equipment and the video footage was analysed with a computer software called PICSCAN, also known as Persias, which was developed by Thompson himself. The relationship he found showed that the movement of one person is affected by the movement of another person moving ahead (Thompson, 1994).

Lam & Cheung (2000) found that pedestrians tend to walk faster outside compared to inside, which was explained as being caused by there being more factors of influence e.g. the weather condition and the vegetation. It was also found that pedestrians walk faster in commercial and shopping areas. This was made in an empirical study with help of time-lapse photography. This was carried out in facilities such as walkways, crosswalks and railway stations in purpose of getting information regarding walking speeds and flows in crowded spaces. The image process was manual and the information that could be derived was limited to walking speed, flows and walking behaviour (Lam & Cheung, 2000).

Cao, et al (2016) performed an experimental study where they investigated properties of pedestrian movement in crowds with different age groups. Two video cameras were recording from above and the participants walked in an, enclosed, circular path in a single file arrangement. The analysis process was conducted with the software PeTrack, which creates a 3D coordinate system. This meant that the cameras did not need to be perpendicular to the path. The experiment was carried out with 80 young students and 47 older adults. Three groups were investigated, younger, older, and mixed, and they found that traffic jams seem to occur more often in a mixed group. They also found that different ages and mobility affect the properties of pedestrian movement and cause a non-uniform system. Furthermore, the lateral movement, or body sway, increased when there were more people in the enclosed pathway (Cao et al., 2016).

It is quite common to conduct experiments where participants walk in an enclosed, circular pathway as Cao, et al (2016) did. Liu, et al (2009) did it as well and found a linear relationship between decreased frequency and amplitude of lateral oscillation, and decreased walking speed. They also found that the velocity during their tests differed from previous, similar research. This led to the conclusion that the velocity is generally higher for taller people (Liu, Song, & Zhang, 2009). This experiment utilised single file movement as well and was recorded from above.

Another example is from Zhao, et al (2017), who in their experiment wanted to investigate self-slowing behaviour in both normal and emergency situations. They found that in both situations, people want to maintain their personal space and in order to do so, they knowingly reduce their walking speed to avoid contact (Zhao, Lu, Li, & Tian, 2017). The video recordings were analysed with an automatic tracking system.

Seyfried, et al (2005) conducted an experiment to investigate the relation between walking velocity and density. This was done with a circular pathway as well, but they had a video camera perpendicular to the path that was recording horizontally in addition to the cameras above. The camera above was a stereo vision camera which could triangulate the image in order to enable the collection of 3D measurements. The analysis of the data from the horizontal camera was done frame-by-frame, while the camera above was done automatically with software that could identify and track objects. They found that the mean value of velocity at different densities collected from the automatic process is comparable to the ones from the manual process. They also concluded that there is a linear relationship between the velocity and an inverse velocity for density (Seyfried, Steffen, Klingsch, & Boltes, 2005).

A major difference in the results collected in the last decades compared to the ones from the middle of 20th century is that later research treats the people moving in crowds as individuals with different characteristics, rather than treating them as a uniform group. This makes the results more applicable for real life scenarios.

2.3 Research using optical motion capture

The use of an optical motion capture system requires sensors on selected body parts. There are systems that uses either passive or active markers. The active markers transmit a signal that is captured automatically by the receiver and give a 3D position, often in real time. These markers can be tracked individually. The passive markers do not send a signal, but the camera captures the reflections from the markers and gives the position automatically (Best & Begg, 2006).

Jelić, et al (2012) did an experiment to distinguish one-dimensional pedestrian traffic at different densities. The 28 participants walked in different densities in a circular path and were tracked by a VICON MX-40 motion capture system. The participants had passive markers placed on the shoulders and on the head, and 12 infrared cameras were used to capture the data from the tests. They came to the conclusion that there are three linear regimes in the relationships between velocity and spatial headway, or inter person distance, divided in free, weakly constrained, and strongly constrained. The transitions between these regimes is at headway distances of 1.1 m and 3.0 m (Jelić, Appert-Rolland, Lemercier, & Pettré, 2012). The markers on the shoulders gave coordinates regarding body sway which in turn were used to get data about the stepping behaviour. They claim that in crowds the step length, rather than the step frequency, is how people adapt their walking speed (Jelić, Appert-Rolland, Lemercier, & Pettré, 2012).

While Jelić, et al (2012) had many people that were walking as a crowd, other in-depth analyses are mostly conducted with one participant at a time. For example, a study where Hackney, et al (2015) investigated if the pass-ability of obstacles changes depending on if the obstacle is a human that is standing still, or a pole. They found that people leave more space and take a greater caution when passing a human, rather than a pole. (Hackney, Cinelli, & Frank, 2015) Another study shows that people require a shoulder rotation when walk through apertures, if it is smaller than their shoulder width*1.3 (Warren & Whang, 1987). However when presented with a choice, people chose to walk around aperture rather than through it if the opening was smaller than their shoulder width*1.4 (Hackney, Vallis, & Cinelli, 2013). The kinematic data in these experiments was collected and measured with an OptoTrak camera system at a sampling frequency of 60 Hz, which supplied the researchers with 3D tracking data. The participants were fitted with three infrared-light emitting active diodes which transmit a signal to a receiver. These were placed on the head, left and right shoulder, and on the position of the centre of mass.

Does the gait strategy change at extreme low walking speeds? This was the question asked when Smith & Lemaire (2018) wanted to assess the relationship between walking speed and common temporal-spatial stride parameters. They used an optical motion capture system, Vicon 3D motion capture, with CAREN-extend virtual environment equipment. 30 participants were used, walking one-by-one on a treadmill at 0.2 – 0.8 m/s. They claimed that step length, stride length and step frequency has a linear relation to walking speed, even at speeds below 0.4 m/s. But that the movement pattern changes at very low speeds (Smith & Lemaire, 2018).

A simple way of determining the mean gait speed is by fitting a person with two passive markers, one on each heel, and having him or her walk on a treadmill. This is what de Sá e Souza et, al (2017) suggested in their study. The data was collected by a motion capture system consisting of 10 infrared cameras, a Vicon nexus (de Sá e Souza et al., 2017).

Following this review, it has been noticed that, in most investigations, the experiments are conducted with one participant at a time. Only Jelić et al (2012) did it with several people in the same test, but with the use of passive markers. An analysis with several participants and active markers has not been found.

2.4 Research using inertial sensors

The previous sections established that human movement studied use different methods. These methods have limitations regarding either the price of the equipment or the space needed to collect the data. The markers that are attached to the body can easily be obstructed by other body parts, which might affect the results (Mayagoitia, Nene, & Veltnik, 2002). Because of this, many researchers have tried to figure out how to use inertial sensors in the recent years, in order to estimate different gait parameter (Díez, Bahillo, Otegui, & Otim, 2018). Diez, et al (2018) made a review of the topic to investigate how far the research had gotten. Even though there are many proposals of how to estimate step length using inertial sensors, the models and assumptions suggested varies. Because of this the method is still in a research stage, but the potential that the inertial sensors have is substantial (Díez, Bahillo, Otegui, & Otim, 2018).

In order to see if the inertial sensors are applicable in the biomechanical field, Kasai et al (2017), conducted an experiment where they attached the sensor, a Waseda Bioinstrumentation Ver. 4, on the lateral side of the shank, right above the ankle. This was to estimate the stride length, and they compared two different methods of orientation estimation together with three algorithms of event detecting. To see whether these estimations is true, they also used a motion capture system where they attached two markers on each ankle bone and four markers on the hip joint. The seven participants were told to walk, one-by-one, at a brisk walking speed. They came to the conclusion that the method using the first cross-zero point of angular velocity together with an orientation method which, in a global reference system, estimates the altitude of the sensor is the one that is best suited for brisk walking speeds. It also coincides better with the results from the motion capture system (Kasai, et al., 2017).

Mayagoitia et al (2002) compared inertial sensors with a motion capture system, VICON. The results showed that the inertial sensors gave almost the same results as the VICON did (Mayagoitia, Nene, & Veltnik, 2002). Again, there is a lot of potential of using this technique and the research in the area goes forward.

2.5 Research using eye tracker

Eye tracking might sound like it is a new technology, however the first device that could track eye movement was built by Edmund Huey in 1908 (Eyesee research, 2014). It was a type of contact lens that had small openings for the wearer's pupil. The lens was attached to a pointer which changed position when the wearer moved his or her eye.

The early methods of measuring eye movements were very intrusive and could nt differentiate between eye movement and head movement (Eyesee research, 2014). This changed in the 1970s when eye trackers were developed that were more accurate, less intrusive, and could in fact separate eye movement from head movement (Cornsweet & Crane, 1972). During the second computer revolution in the late 1970s and early 1980s (PC Magazine, Accessed 2019) computers became powerful enough to perform eye tracking in real time, which lead the way for the application of video-based eye trackers to human-computer interaction.

Eye tracking has been used in marketing since the early 20th century. The first eye movement analysis of printed ads that we know of was conducted in 1924, by observing consumers who were reading a magazine with printed ads in it. To do this, the observer had to hide in a box behind a curtain (Wedel & Pieters, 2015). In 1978, J. Edward Russo wrote an article, *"Eye-fixations can save the world",* in which he argued for studying eye movements, focusing on consumer decision processes, to evaluate marketing effectiveness (Russo, 1978).

At the end of the 1990s, companies started using eye tracking technology to observe reactions to internet content. The main reason for these studies was the growing potential of the online products- and service market (Eyesee research, 2014). Until then, a majority of web designers used the same layout used in newspapers in their web design. The term "*Google's Golden Triangle"* describes a triangular area with intense eye scan activity that occurs the first time a person visits a new google search results page (Hotchkiss, Alston, & Edwards, 2005). Generally speaking, if the listing is not in the Golden Triangle, the odds of it being seen is dramatically reduced.

Since the 2000s until today, eye tracking technology has continued to evolve, and has been applied to a wider range of sciences. For example, it has been used to show that the difficulty children with autism spectrum disorder, ASD, have in using social cues such as gaze to aid word learning is likely due to a reduced preference for the object being looked at (Akechi et al., 2011). It has also been evaluated as a means of forensic analysis of pedestrian falls, where it proved a useful utility in some situation-specific conditions (Kuzel, Cohen, Rauschenberger, & Cohen, 2013).

There have been studies in the field of human behaviour during egress as well. For instance, the lighting of a corridor was shown to be of importance when identifying possible egress routes. A highly lit corridor drew the attention faster than corridor that was dimly lit (Noriega, Vilar, Rebelo, Pereira, & Santos, 2013) (Rostedt & Andersson, 2019).

When studying wayfinding, it was shown that males could find unclear exit signs in a comprehensive environment more easily than females, but there was no discernible difference if the signage was instantly recognisable (Y. Liu, Sun, Wang, & Malkawi, 2013). This was done with an experiment where the participants were presented with pictures of decision-making points from various public buildings, while wearing eye tracking equipment. They were asked to search for the building exits or the exit directions and each photo was presented for 5 seconds. Furthermore, results from a different experiment conducted by Till & Babcock (2011) indicated that people who followed the emergency exit signage had significantly lower egress time compared to the people that didn't use the signage at all (Till & Babcock, 2011). During this experiment the participants were asked to locate a doorway that would take them outside of the building, take a picture of it, and then return to the starting point.

In a study conducted by Franchak & Adolph (2010), in which they investigated the spontaneous eye movements in children and adults during self-initiated locomotion through a cluttered environment, it was found that both children and adults can navigate past obstacles without having to fixate on it, relying on their peripheral vision (Franchak & Adolph, 2010). Futhermore, it was shown that the use of peripheral vision to navigate obstacles increases with age (Franchak & Adolph, 2010).

An interesting thesis presented by Björkqvist & Broholm (2017) investigated how alcohol affected peoples' tendency to evacuate. They showed that there was no significant difference between sober people and people under the influence of alcohol regarding the number of people that chose to evacuate during their experiment (Björkqvist & Broholm, 2017). The participants' alcohol blood content was around 0.3 ppm. In this case, the eye tracker was used to see if there was any difference between the groups in regard to how many different stimuli they noticed. Examples of the stimuli used are exit signs and fire doors.

Studies have been conducted to establish how people find their way out of a building and if they notice the fire safety elements, such as emergency exit signs and emergency doors, when doing so. However, there is little research regarding what affects the decision-making that occurs when people move through a crowd of people.

3 Theory regarding human movement

This chapter is aimed at explaining elements of human movement that are relevant to this thesis.

3.1 Gait cycle

The step length and stride lengths are part of the gait cycle and to better understand the graphs in the result chapter, it is good to also know other parts of the gait cycle.

The gait cycle consists of occurrences and phases, where an occurrence is something linked to a specific time and a phase is linked to a duration. The most important occurrences are the heel strike and the toe-off. The heel strike is the moment when the heel touches the ground and the toe-off is the moment when the toe loses contact with the ground. The phases are double support, single support, stance, swing, step and stride. (Birch, Vernon, Walker, & Young 2015) The phases of a right leg's gait cycle are illustrated in Figure 2. Note that it is not to scale.

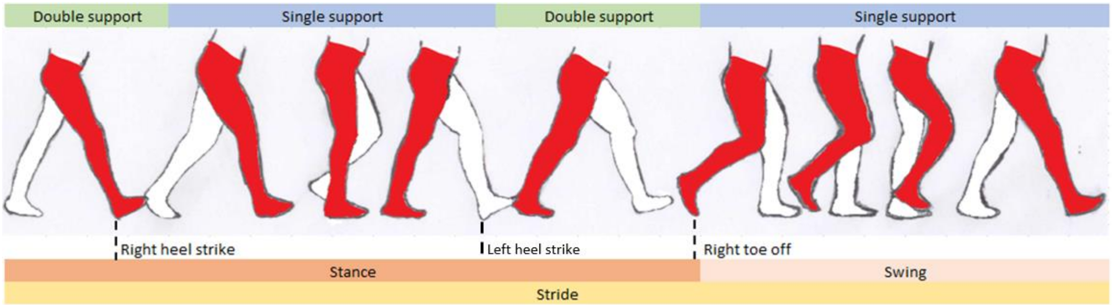

Figure 2 - The occurrences and phases during a gait cycle, focusing on the right limb

A stride constitutes the gait cycle, and is the movement of both the right and left limb and it is the distance between two subsequent heel strikes performed by the same foot. During a stride, both double and single support occurs twice. The double support is the duration of when both feet touch the ground and the single support is, accordingly, the duration when a single foot is in contact with the ground. The stride can also be defined as a combination of stance and swing phases. The stance phase is a support phase where the foot is in contact with the ground and gives support to the body. This phase usually represents 60 % of the duration of the stride. The swing phase starts with the occurrence of toe-off and ends at the heel strike. This phase gives balance to the body and represents about 40 % of the duration of the stride (Best & Begg, 2006), (Birch, Vernon, Walker, & Young , 2015) and (Oatis, 2004).

During a stride there are two steps, one left step and one right step. The length of a step is measured from a heel strike on one foot to the heel strike of the other foot which is illustrated in Figure 2 and Figure 3. The left step length is not necessarily the same as the right step length in normal walking, which is why you usually talk about right step length and left step length (Best & Begg, 2006) and (Birch, Vernon, Walker, & Young , 2015).

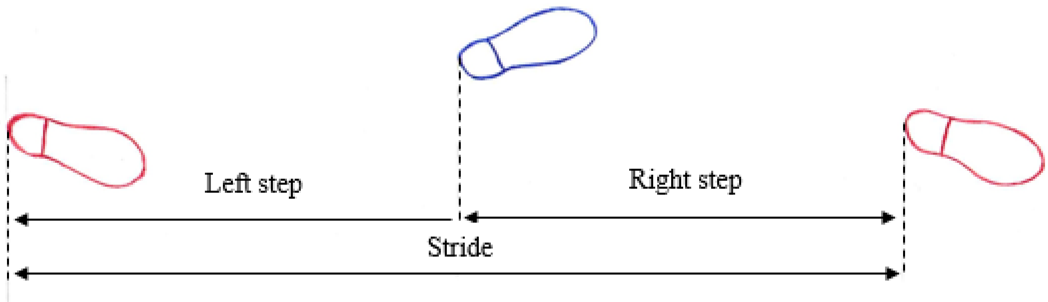

Figure 3 - Illustration of the right step and left step, forming a stride

3.2 Crowd movement

The appearance of crowd moving forward in the horizontal plane varies. It is possible to divide these appearances into three categories, laminar, turbulent, and stop-and-go flow. The density of the crowd is often the cause for a change from laminar flow into either stop-and-go- or turbulent flow (Helbing, Johansson, & Habib Zein, 2007). The laminar flow is characterised by an even flow where the pedestrian walks unhindered in the direction they choose to walk, e.g. when walking into a classroom. A stop-and-go flow can be thought of as something similar to the flow of cars in a single lane queue. When a car starts moving the car behind will accelerate, often to a speed which is too high to create an even flow, meaning that they have to use the brakes (Ranney, 1999). This triggers a chain reaction in which the cars behind will break, sometimes to a full stop. The pedestrian, or in this case car, can still move in the direction they chose. Unlike both the laminar and stop-and-go flow, the turbulent flow is characterised by its movement along two axes, where the people are moving not only forward but to the side as well. Much like the movement near the stage at a concert. Illustrations of the three appearances can be seen in Figure 4.

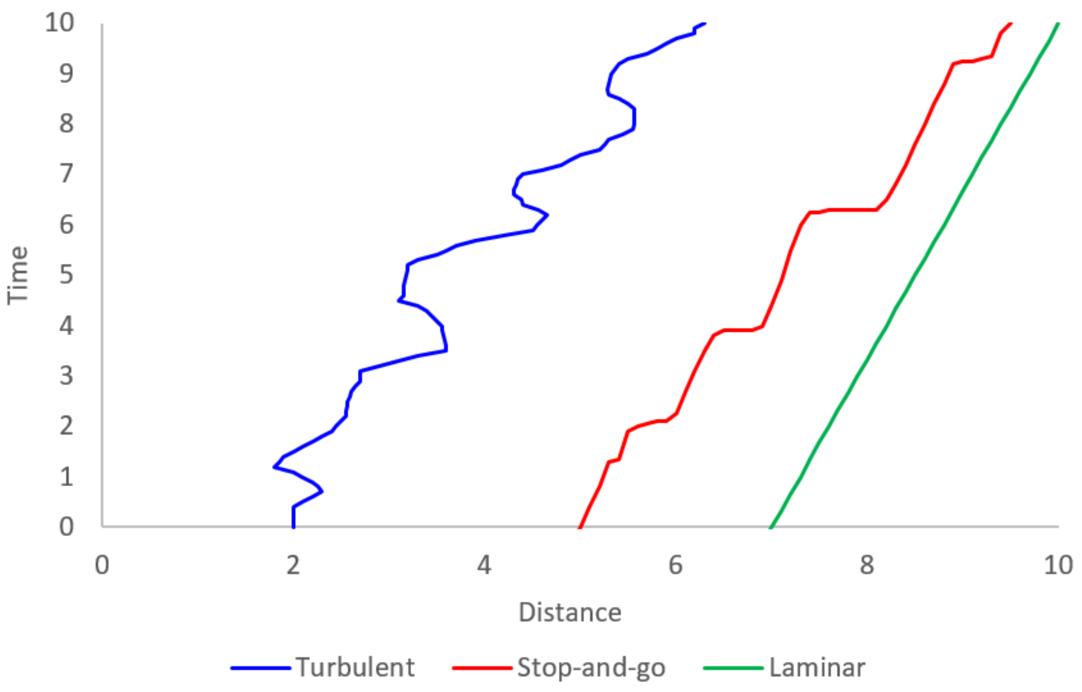

Figure 4 - Illustrations of the three crowd movement appearances

When the density of a crowd increases, the distance between the people decreases. When the flow becomes less than 0.8 ped/m/s the likelihood of stop-and-go waves increases (Helbing, Johansson, & Habib Zein, 2007). This stop-and-go behaviour seems to occur due to the fact that people look around themselves more often at lower speeds and when they do, their attentiveness is lowered and they might collide with the person in front, or at least stop. This will then influence the person behind (Friberg & Hjelm, 2015). The waves can occur in different places simultaneously, and some people stop while others slow down (Portz & Seyfried, 2011).

In crowded spaces where the density is even higher, people might lose the ability to move forward by their own terms. This is what is characterised as turbulent flow. It is an irregular flow in which people are pushed around in every possible direction, even against their will. It is in this state of motion that disasters may happen, where people that fall get trampled if they cannot get back on their feet quickly enough (Golas, Narain, & Lin, 2014) and (Helbing, Johansson, & Habib Zein, 2007).

3.3 Inter person distance

The inter person distance is defined as the distance from the centre of the body of one person to the centre of the body of another person (Bae, Lee, Choi, Yoon, & Hong, 2014), (Thompson & Marchant, 1994). This is illustrated in Figure 5. A different way of seeing inter person distance is headway including a safety margin, which is the space needed to avoid contact to the person in front (Hansen, 2018).

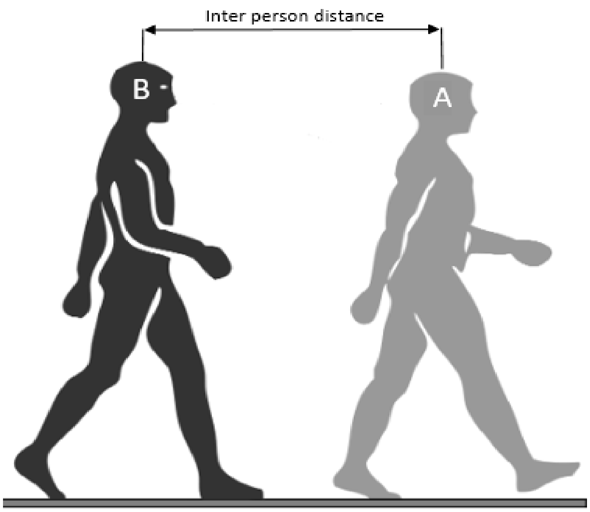

Figure 5 - Illustration of inter person distance

3.4 Body sway

The human body is an unstable system and the reason for this is that major part of the mass is located in the upper part of the body. In fact, the head, arms and trunk make up two thirds of the body weight, and they are located in the upper two thirds of the body height (Winter, MacKinnon, Ruder, & Wieman, 1993). This is why a balance system is needed, to prevent falling. Ba lance is the ability to maintain stability of the body and to maintain the centre of gravity within the base of support (Jannet, 2008). The base of support is the area between and beneath the feet that is in contact to with ground, see Figure 6. To maintain balance the centre of gravity must stay in that area, meaning that a bigger base of support gives more stability to the body (Mooney, 2009). Centre of gravity is the midpoint of a body´s mass and the point in the body where all parts are in equilibrium. It is the vertical line from this point that will be maintained in the base of support area (Steadman, 2012).

Figure 6 – The base of support, highlighted in yellow

As Figure 2 describes, a gait cycle contains two double support phases and two single support phases. The double support phases make up 20 % of a cycle. During a double support phase, the centre of gravity is located between the feet (Winter et al., 1993). But during the other 80 % of the stride, the base of support is only one foot and the centre of gravity does not necessary lie within that area (Kharb, Saini, Jain, & Dhiman, 2011). This means that the body needs to correct the point of balance, which is done by what is called body sway. This body lateral sway decreases when the walking speed increases (Chen, Lo, & Ma, 2017).

3.5 Contact distance

Contact distance is defined as the distance between a body part of one person to a body part of the obstructing person which is shown in Figure 7. The minimum contact distance is the most crucial as it's the shortest distance between the persons. This means that the minimum contact distance is the amount of available space possible for movement towards the person ahead (Thompson & Marchant, 1994).

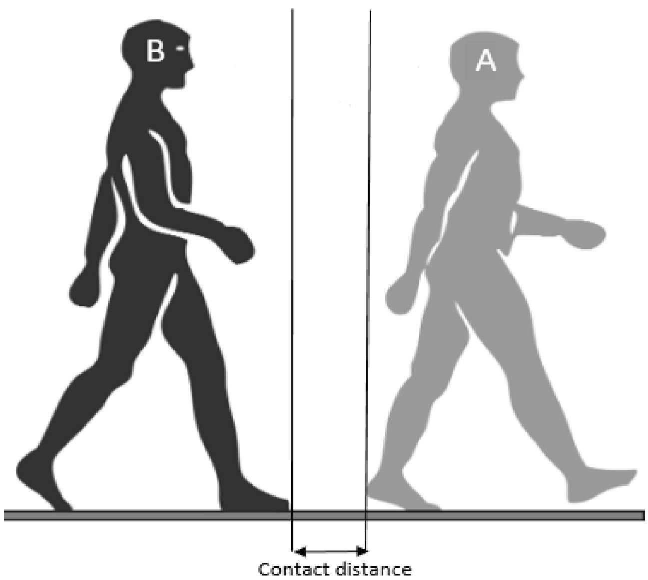

Figure 7 - Contact distance between two persons walking behind each other

4 Experiments

This chapter describes the different experiments conducted during this thesis. It describes how participants were recruited, which equipment was used, the preparations and set-up of the experiment, the order of the tests and how the analysis of the collected data was performed. Firstly, the experiments in Lund, Sweden is described before moving on to the experiments in Dublin, Ireland.

4.1 Video capture and eye tracker

Prior to the main experiment, a pilot test was held in order to test the suggested setup and address potential problems. The pilot was held in a large room at "Laurentiistiftelsen" in Lund, and the main experiment was held at the student union building, Kårhuset, at Lund University. The main experiment was conducted on the 17th of October 2018.

Figure 8 illustrates the general workflow for a video capture experiment, from the preparations prior to the experiment to the clean-up and sorting of the collected data.

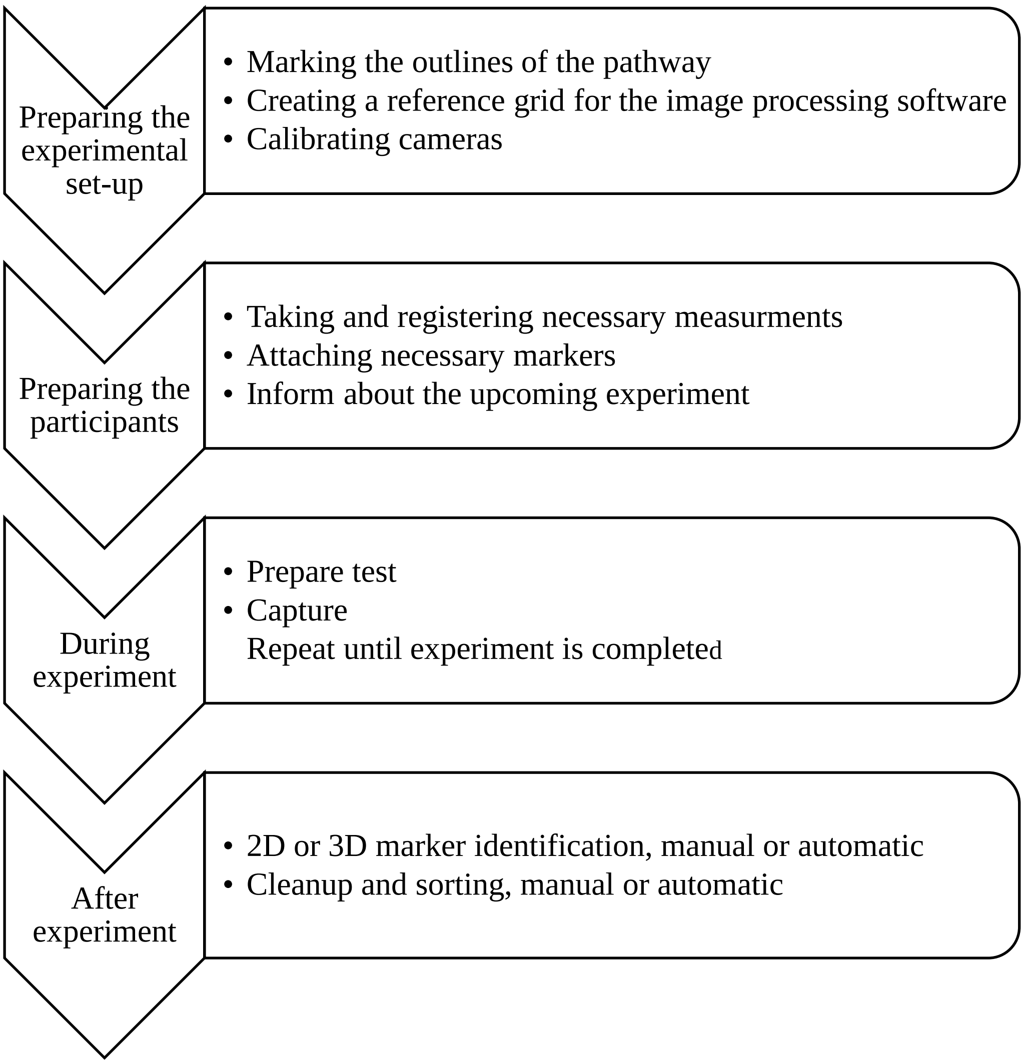

Figure 8 - General workflow for a video capture experiment

4.1.1 Participants

A majority of the participants of the experiment were students from the Faculty of Engineering at Lund University in Lund, Sweden. These students were recruited during lectures in the week prior to the experiment. The other participants consist of neighbours, friends and friends-of-friends of the authors which, although not students at LTH, were still students at either Lund University or Malmö University. Their ages ranged between 17 and 29 years, with an average age of 20 years with a standard deviation of 2.0 years, and their heights ranged between 1.60 and 2.02 m, with an average height of 1.80 m with a standard deviation of 0.103 m.

During the recruitment process different lecturers were contacted to get permission for the authors to give a short presentation at the start of their lectures. During the interval the students were able to get further information from the authors and then sign up for the experiment. They were told that the experiment was aimed at evaluating how people move in crowded spaces. Details on what information would be analysed was left out, and the eye tracking equipment was described as glasses with a built-in video camera. The motivation for this was that if the participants knew the actual function of the equipment, it might have affected the results. However, many of the participants had heard about eye tracking by word of mouth from friends that had taken part in other experiments at LTH that utilised this type of technology. The effect this might have had on the results will be discussed later in the thesis. As a means of motivating the students to sign up, a free ticket to the cinema was offered as a compensation for their time.

The distribution of participants that attended was 14 people in the pilot test and 59 people in the main experiment. A total of 109 people signed up for the experiments, which gives a falling-off rate of roughly 33 %.

4.1.2 Equipment

A variety of different equipment was used during the preparation and execution of the experiment. Table 1 lists the equipment together with a short explanation of their purpose. The eye tracking equipment with its related software will be given a more thorough introduction.

Table 1 - Equipment used during the experiment in Lund, Sweden

Equipment	**Purpose**
Measuring tape and a folding rule	To measure out the path, as well as measuring the participants
Different kinds of tape	To mark the outline of the path and the positions of the cameras, as well as creating a grid on the floor that would be used as points of reference in the analysis
A vertical pole with a known, fixed length	To use as a point of reference in the corners of the grid. This was not used in this analysis, but it enables further analysis of the collected data.
Chairs and tables	To create barriers around the marked path so that the participants stay within the parameter of the path.
Rope	To create a “clear” barrier so that the participants stay within the parameter of the path, while still allowing the video cameras to capture as much of the participants profile as possible.
Movable walls	To wall-off the two straight sections of the path from each other to minimise distractions.
Tags with numbers and rubber bands	To assign each participant a specific number that would be linked to their measurements, so that they can be identified during the analysis. The rubber bands are used to attach the tags to the arms of the participant.
Markers	To enable specific points of interest on the participants to be followed during the analysis
A computer	To register the participants measurements as well as functioning as a notepad during the experiment.
Three video cameras and tripods	To record the entire experiment from different angles. Two models of SONY video cameras were used, one HDR-PJ780 and two HDR-CX220.
Eye tracking equipment	To collect data on what the participants are looking at while moving along the path.

Eye tracker

The eye tracking device is a technology that can track what people are looking at in real time, while they move freely in any real-world setting (Tobiipro, Accessed 2018). Because of this, they can be used to answer questions such as: “How long does it take before this person notices the stop sign?”; “When walking up or down a staircase, where does the person fixate their eyes?”, “Does the person notice this type of visual cue faster than another one?” or “What does the person look at when planning how to get through a crowd?” This ultimately increases the knowledge of how people react to their environment. The glasses are shown on the right-hand side of Figure 9, while the recording unit is on the left-hand side.

Figure 9 - The eye tracking equipment used in the experiment

There are two types of eye movement, saccades and fixations. Saccades are the type of eye movements that moves the gaze from one point of interest to another, while a fixation is a period of time where the eye is kept aligned with the point of interest for a certain duration in order to process the image details (Tobiipro, Accessed 2019).

However, this does not mean, even if the glasses register a fixation, that the person has registered any change. It has been observed that, in normal lighting, most people need to see a word for 50-60 milliseconds to perceive it, while they need to look at a picture for more than 150 milliseconds to interpret what they are seeing (Tobiipro, Accessed 2019).

Tobii Pro Lab

The software that is used by the Eye Tracking device is called Tobii Pro Lab. It is divided into three modules: designer, recorder, and analyser.

In the designer module the user can customise experiments based on timelines with different stimuli. The stimuli can then be edited with multiple settings, e.g. display position and presentation time (Tobiipro, Accessed 2018).

The recorder module is used to configure the eye tracker, i.e. calibrate and record eye tracking data.

In the analyser module, the user can replay, visualise and analyse the recorded data. The data can also be exported to enable further processing in third-party software e.g. Microsoft Excel.

4.1.3 Experimental set-up

Before the participants arrived, the experimental set-up was prepared. The cameras were placed perpendicular to the plane of motion, which can be seen in the left picture in Figure 10. One camera was placed on the inside and one on the outside of the circular path, and one was placed above one of the straight sections. The finished setup is shown in the right picture of Figure 10. The path is 0.8 meters wide and has a central circumference of 20.56 meters.

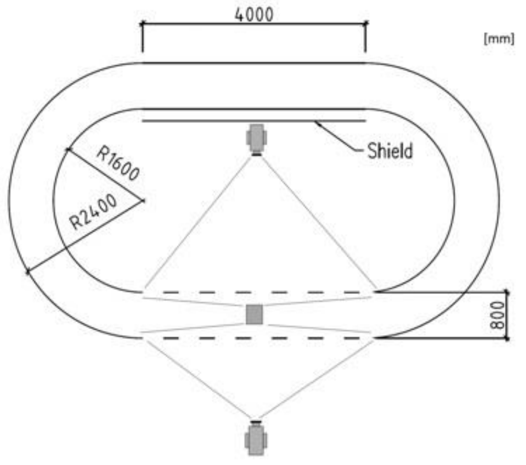

Figure 10 - L. Schematic of the pathway with the camera placements. R. Picture of the finished set-up

In addition to preparing the path, a measuring station was established where the participants would be measured and fitted with markers on different points of interest. They were also assigned a number that was tied to their measurements. This number was attached on their arms with rubber bands, so that they would be clearly visible for the cameras. This can be seen in Figure 11 along with one of the markers. Figure 12 then shows where the markers were attached, and which body parts were measured.

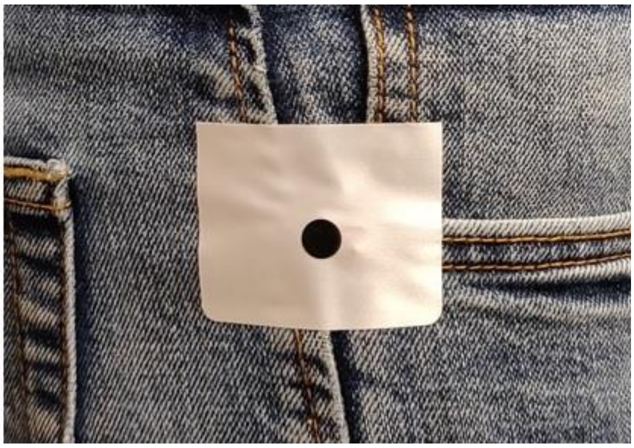

Figure 11 - L. An example of how the number was attached. R. A marker used during the experiments

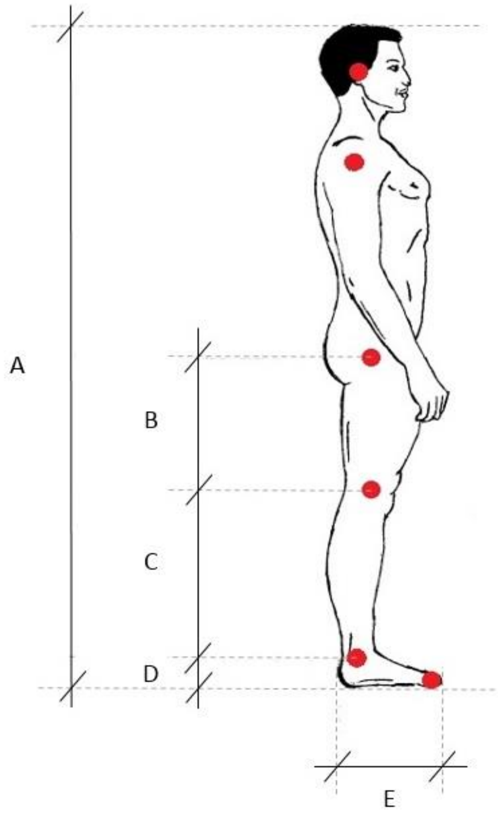

Figure 12 - Where the markers were attached (red dots) and what was measured on the participants

4.1.4 Order of tests

After being measured, all the participants were asked to walk along the path one by one in order create an unhindered reference speed. They were asked to walk at a speed which they consider a normal speed.

Table 2 presents the different tests together with the variations that occurred. In all the tests the participants were asked to walk as they would normally do when there is this amount of people present (the current occupant density) without overtaking. The tests were divided into two variations, single and double file. A single file arrangement means that the participants were only allowed to walk in single line and a double file arrangement means that the participants could walk in two separate lines. To understand the different categories in the table, the following list is provided.

- **Attendance** – Number of participants that were in the test
- **Arrangement** – Explains if it's double or single file
- **Density** – Density derived from the attendance. The unit depends on the arrangement, Single file has [ped/m] while double file has [ped/m^2]
- **Eye Track set-up** – explains how the eye tracker was varied. The letter that is bold is the participant using the eye tracker, followed by the three people in front of him/her. A 'T' means that it's a taller person and an 'S' means that it's a shorter person.

Table 2 - Order of tests during the video capture experiment, with information regarding variations. Use with the list presented on the previous page (20)

Test	Attendance	Arrangement	Density	Eye track set-up
A1	59	Double	3.59 ped/m^2	**T**-S-S-S S-S-S-S
A2	59	Single	2.87 ped/m	*
A3	59	Single	2.87 ped/m	**T**-S-S-S
B1	49	Double	2.98 ped/m^2	*
B2	49	Single	2.38 ped/m	*
B3	49	Single	2.38 ped/m	**S**-T-T-T
C1	39	Double	2.37 ped/m^2	**T**-S-S-S S-T-S-S
C2	39	Single	1.90 ped/m	**T**-S-S-T
C3	39	Single	1.90 ped/m	**T**-S-S-T
D1	29	Single	1.41 ped/m	**S**-S-T-T
D2	29	Single	1.36 ped/m	*
D3	29	Single	1.41 ped/m	**S**-S-T-T
E	59	Double	3.59 ped/m^2	**S**-T-T-T S-S-T-T
F	59	Single	2.87 ped/m	*
G	24	Single	1.17 ped/m	**T**-S-T-S
H	24	Single	1.17 ped/m	**S**-T-S-T
I	24	Single	1.17 ped/m	**S**-T-S-T
J	24	Single	1.17 ped/m	**T**-T-S-T
K	19	Single	0.92 ped/m	**S**-S-T-T
L	24	Single	1.17 ped/m	**S**-S-T-T

*Due to technical difficulties with the eye tracking device, no data was recorded.

4.1.5 Process of analysis

This section explains how the analysis process of the video capture and eye tracker data was conducted, starting with the video capture data and ending with the eye tracker.

Video capture

The analysis of the data from the video capture experiment was conducted in Kinovea, which is a free, open source video player developed for sport analysis. The software can be used to track points of interests, e.g. knee joints, and how their positions changes throughout the recording. Further examples of what it can be used to measure is distances, angles, time spans, speeds etc. (Kinovea, n.d.)

The first stage of the process was to cut the videos into 20 smaller videos, one for each test. An image distortion error from the video cameras needed to be addressed, which was done with the software Adobe Premiere. The distortion problem was larger than expected and in order to see all the markers on the participants, some of the problem could not be resolved. The size of the distortion removal was -10 pixels. Since Kinovea only gives measurements in one plane, there is an error in measurement depending on how offset from the centre line the participants walked. Figure 13 show the size of the errors. The lines are derived from the reference grid that was established before the experiment started. The middle line is the centre while the upper and lower lines are further away and closer to the camera respectively. The distance between the lines are 0.5 m and the measured distance was 1 m.

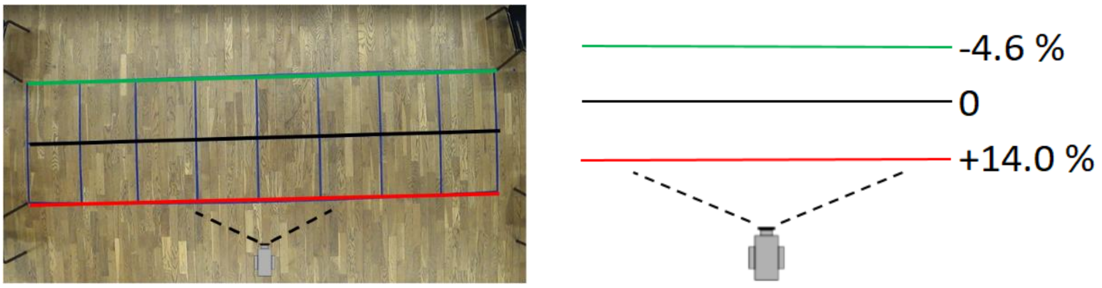

Figure 13 – The size of the offset error

Since the cameras were not moved after they were turned on, the footage of the reference grid could be uploaded into Kinovea as an image. The image was positioned over the desired video and given a transparency of 50% so that the participants' feet were still visible. The next step was to calibrate the video so that measurements could be taken, this was done between the outer lines of the grid, which were four meters apart. Following this, a coordinate system was established to track the change in position of the participants' markers over time.

The expectation was to let the software track the markers automatically, but this did not go as planned due to reflections, intermittently obstructed markers and poor video quality. Instead, the tracking had to be done manually, frame by frame. The process was very time consuming, it took roughly 50 man-hours to analyse the data included in this report. The only actual marker tracked was the hip marker, but aside from this, coordinates for the posterior, anterior, heels and toes of both feet on each person was measured. This was only done in the plane of motion, so any perpendicular change was disregarded.

The analysed section can be seen in Figure 14.

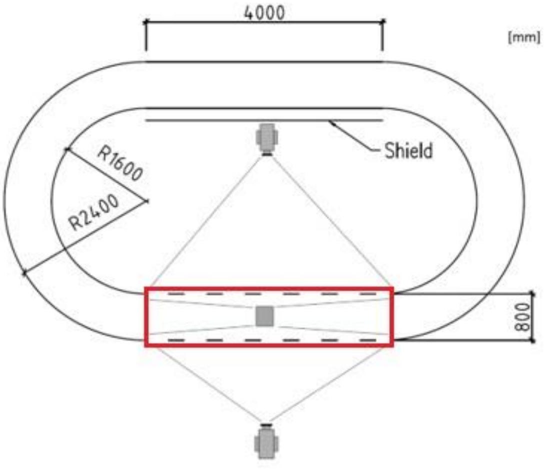

Figure 14 - Illustration of the analysed area

Eye tracker

The analysis was conducted with the software Tobii Pro Lab, which was described in section 4.1.2 The program processes the video received from the Eye track glasses and registers the points were the participant has fixated his or her gaze. The user can then go through these points and see what the person has looked at. An image showing potential areas of interest where the participant might be looking was created and uploaded into the program. This image was then used to create areas of interest, which can be seen as clickable buttons, in the program. Each gaze fixation was then assigned to the different areas of interest, creating a database containing the number of times the participant has looked at the different areas. The analysis was limited to the area highlighted in Figure 14 in order to be consistent with the analysis described in section about video.

Figure 15 shows an example of the image being used within the program. On the left-hand side, the analysed video from the eye track glasses can be seen, and on the right-hand side the created image with the different areas of interest is shown. The circle in the video is where the participant's gaze is focused, and the circle on the image is where the gaze has been registered.

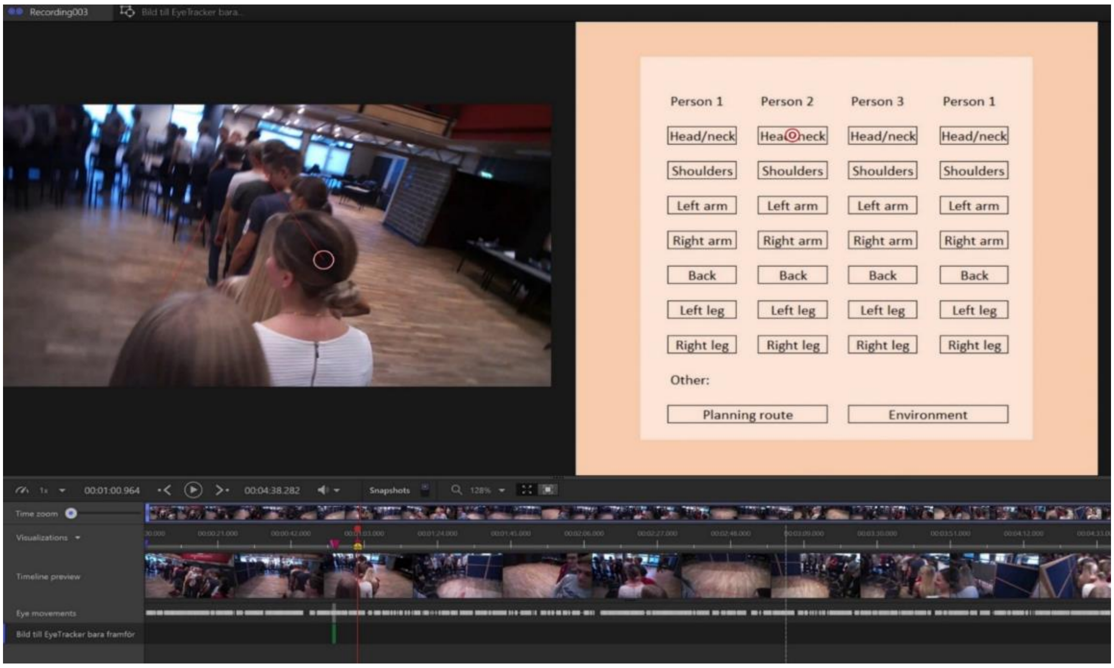

Figure 15 - The image being used in Tobii Pro Lab

Figure 16 explains how the different areas of interest are defined. A note is that if the participant is looking at any person that is ahead of "Person 3", it is registered as "Planning Route" and if he or she is looking at anything behind him or her, it is registered as "Environment". Finally, Figure 17 clarifies the areas of interest on Person 1, 2 and 3.

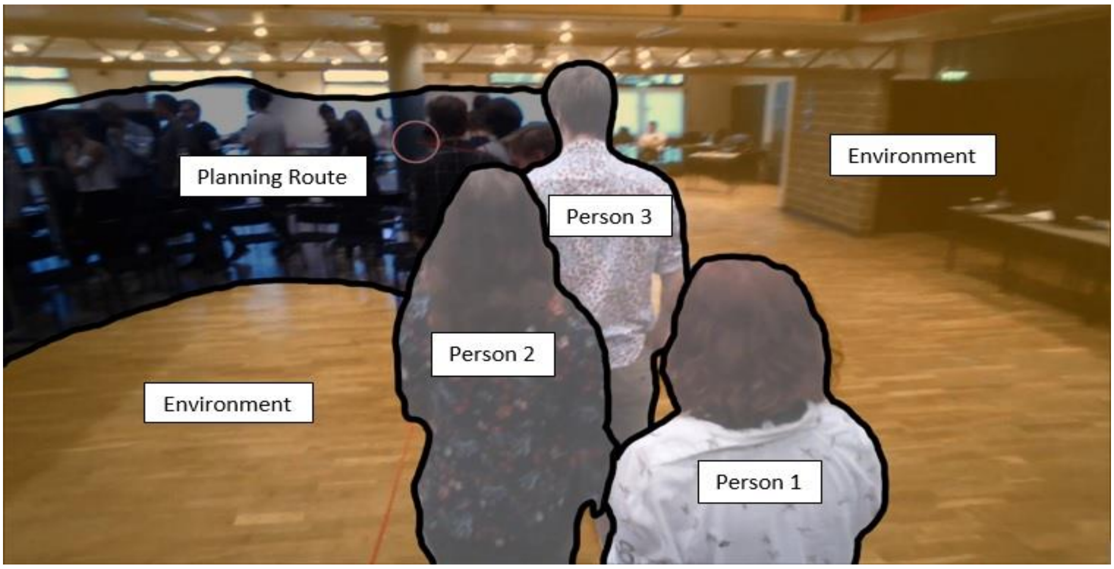

Figure 16 - Definition of the areas of interest used for the eye tracking analysis

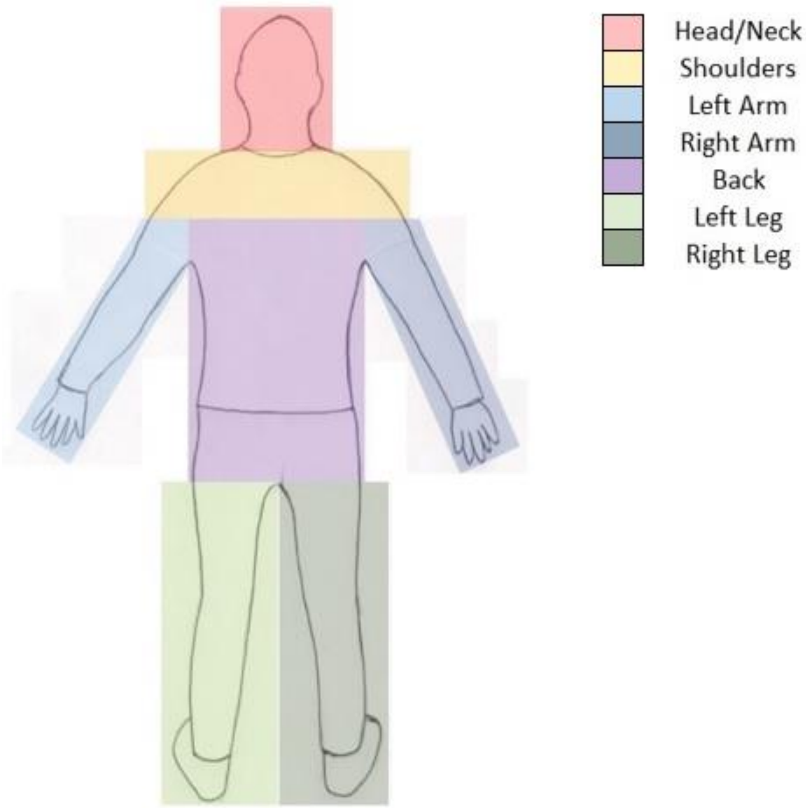

Figure 17 - Definition of the areas of interest on each person used for the eye tracking analysis

In section 4.1.2 it was mentioned that the time needed to perceive different objects varies, but an assumption was made that all fixations detected by the glasses would be considered as a point where the participant had looked at and perceived the object or area. This will be discussed in section 6.1.2.

4.2 Motion capture and inertial sensors

Four groups participated on the experiment at the Movement Analysis Laboratory at UCD School of Public Health, Physiotherapy & Sports Science in Dublin, Ireland. The first group served as a pilot but considering that only minuscule alterations were made to the tests for subsequent groups, this pilot was considered as a part of the main experiment. The experiments were conducted on the 4th, 5th, 7th and 8th of December 2018.

Figure 18 illustrates the general workflow for a motion capture experiment, from the preparations prior to the experiment to the clean-up and sorting of the collected data.

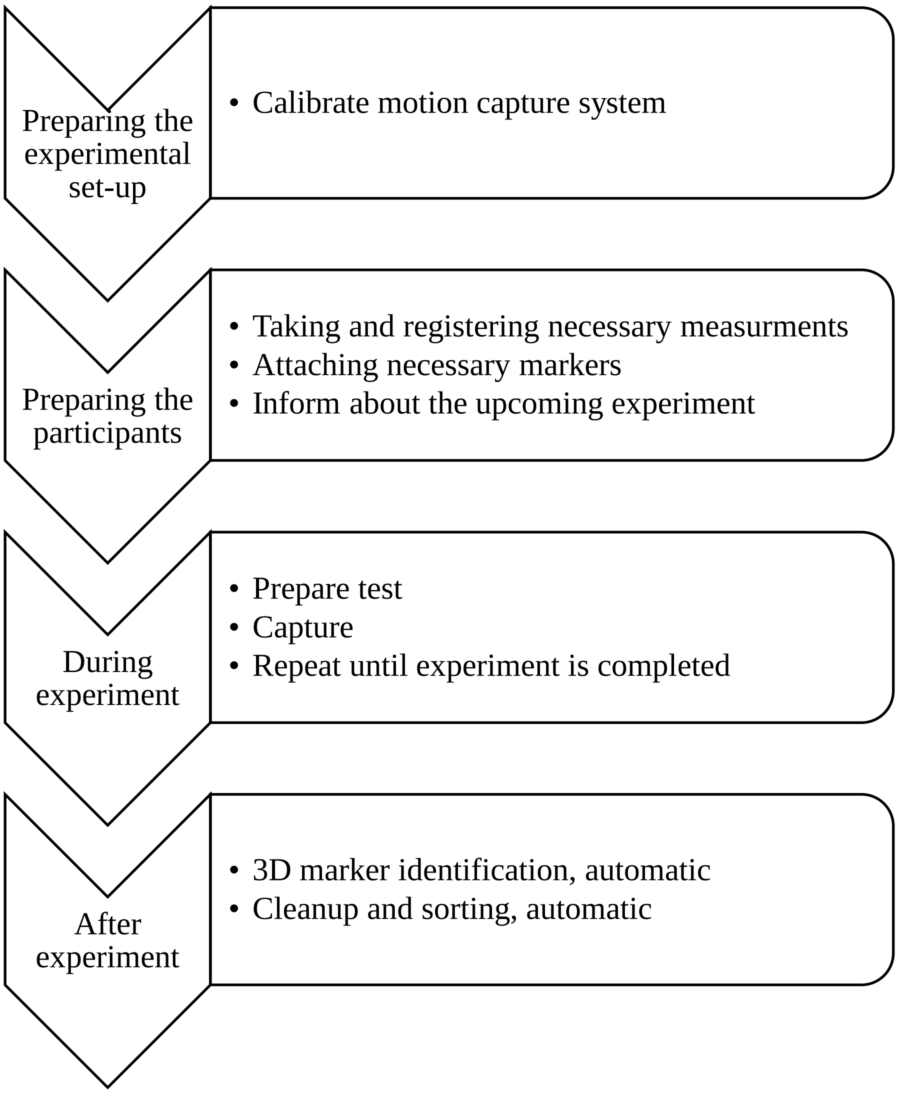

Figure 18 - General workflow for a motion capture experiment

4.2.1 Participants

A total of 16 participants were recruited by the University College of Dublin, UCD. The participants' ages ranged between 25 and 48 years, with an average age of 31.5 years with a standard deviation of 6.74 years. Some of them worked at the college, some were working outside the school and some of them were PhD students. Recruitment was mainly done via a recruitment poster, but also with subsequent word-of-mouth from participants who completed the test.

4.2.2 Equipment

A variety of different equipment was used during the preparation and execution of the experiments. Table 3 lists the equipment together with a short explanation of their purpose. The motion capture system, the Codamotion system, and the inertial sensors will be given a more thorough introduction.

Table 3 - Equipment used during the experiments in Dublin, Ireland

Equipment	**Purpose**
Measuring tape	To measure the participants' shoe, leg and upper arm length, shoulder and hip width as well as their waist circumference and height
Data sheets	To register the participants' measured data
Ruler	To measure the participants' reaction time
Stopwatch	To measure the participants' preferred walking speed
Scale	To measure the participants' individual weight
Different kinds of tape	To attach the different sensors to the participant's as well as mark the position of the camera
Video camera and tripod	To record the entire experiment. The model used was a SONY HDR-PJ780
Codamotion system. Three sensor units (receivers) and 24 markers were used	To capture the participants' movement during the experiments. The models used were CX1 CODA Sensor Units and standard CX markers
Inertial sensor (Shimmer). Four units were used	To capture the participants' acceleration and direction during the experiments. The model used was Shimmer 3 EMG units

Optical motion capture system – Codamotion

A Cartesian Optoelectronic Dynamic Anthropometer (CODA) motion capture system consists of three parts; transmitters, receivers and data analysis software. The transmitters are active markers that are attached to areas of interest, whose position are then picked up by the receivers, also called “sensors. The data analysis software, CODA motion ODIN, will then analyse the data from the receivers and record a three-dimensional cervical range of motion (Gao et al., 2017). Figure 19 shows three receivers while Figure 20 shows two markers along with a battery pack.

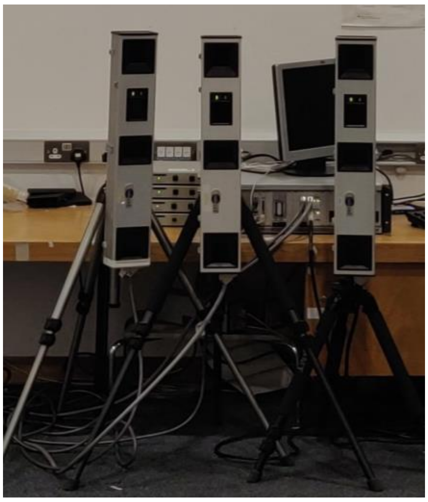

Figure 19 - Three Codamotion receivers

Figure 20 - Two Codamotion markers and a battery pack

In order to start measuring, the user must place three markers on the ground. These will establish in which directions the X- and Y-axis are, with the Z-axis being vertical. The different receivers are then synchronized to create a measured volume, this means that if more than one receiver can detect a marker, this marker will only get one position in the measured volume. This means that the number of receivers determines the size of the measured volume.

Inertial sensor – Shimmer

An inertial sensor is a device that combines a three-axis accelerometer with a three-axis gyroscope to obtain position and orientation information. An accelerometer measures the earth’s gravity and the sensor’s acceleration i.e. the external specific force acting on the sensor, while the gyroscope measures the rate of change of the sensor’s orientation i.e. sensor’s angular velocity (Kok, D. Hol, & B. Schön, 2018). To combine the measurements from an accelerometer and a gyroscope in order to obtain position and orientation information is called “dead reckoning” and is widely utilised in automotive navigation systems (Furuno, n.d.)

Figure 21 shows the process of obtaining a position from the inertial sensor with an integration method. The angular velocity from the gyroscope is integrated to obtain an orientation. This information is added to the external specific force, which establishes if there has been any rotation, and then the earth’s gravitational force is removed. This leaves an acceleration which is converted to a position after two integrations.

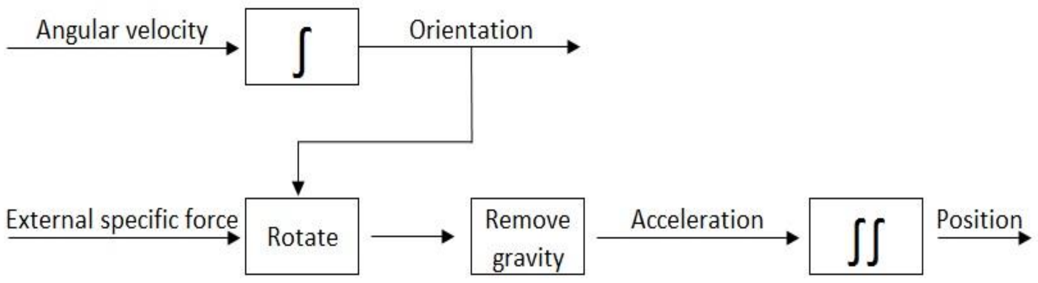

Figure 21 - How the integration method is used to obtain a position

The method of integrating the acceleration twice is a good way to estimate e.g. step length. There is, however, a positioning error known as drift caused by the micro electro-mechanical systems (MEMS). Drifting causes the distance error to grow cubically in time, which needs to be taken into account. There is also difficulty getting the forward acceleration because of body sway, which makes keeping the inertial sensor parallel to the direction of travel. It is then important to always know the orientation of the sensor, which is done by utilising multiple accelerometers and gyroscopes that transform the data into a navigation reference (Díez, Bahillo, Otegui, & Otim, 2018).

A different method is biomechanical, where the estimation of the step length is based on geometrical relations between angles, dimensions, and displacements of different body parts. The advantage of this method is that it allows a good understanding of which relationships the estimation of step length is built on (Díez, Bahillo, Otegui, & Otim, 2018).

The inertial sensor that will be used in the experiment is called a Shimmer unit. Figure 22 shows one of these units attached to the lumbar region, i.e. the lower part of the back, of a participant.

Figure 22 - The Shimmer unit attached to one of the participants

4.2.3 Experimental set-up

The preparations on the day of the experiment started by establishing a clear path for the participants to walk. Then, the three Codamotion receivers were aligned and synchronised, and the video camera was placed, perpendicular to the path of motion, at the maximum distance allowed for it to capture as much of the measured volume as possible.

Four measuring stations were established, Table 4 describes the function of each station.

Table 4 – Description of the function of the stations in the experiments in Dublin, Ireland

Station	Function
1	Measuring • Reaction time using the ruler drop test*
2	Measuring • Height and weight without shoes • Preferred walking speed**
3	Measuring • Upper arm, leg and shoe length • Shoulder and hip width • Waist circumference
4	Attaching • Codamotion markers on both feet, and on the right shoulder • Shimmer unit on the lower back

* A description of the ruler drop test can be found in Appendix A.

** The participants were told to picture a scenario where they are going to lunch and walk in a speed that they would normally do in that scenario

Figure 23 shows how and where the markers were attached on each participant and the finished set-up is shown in Figure 24.

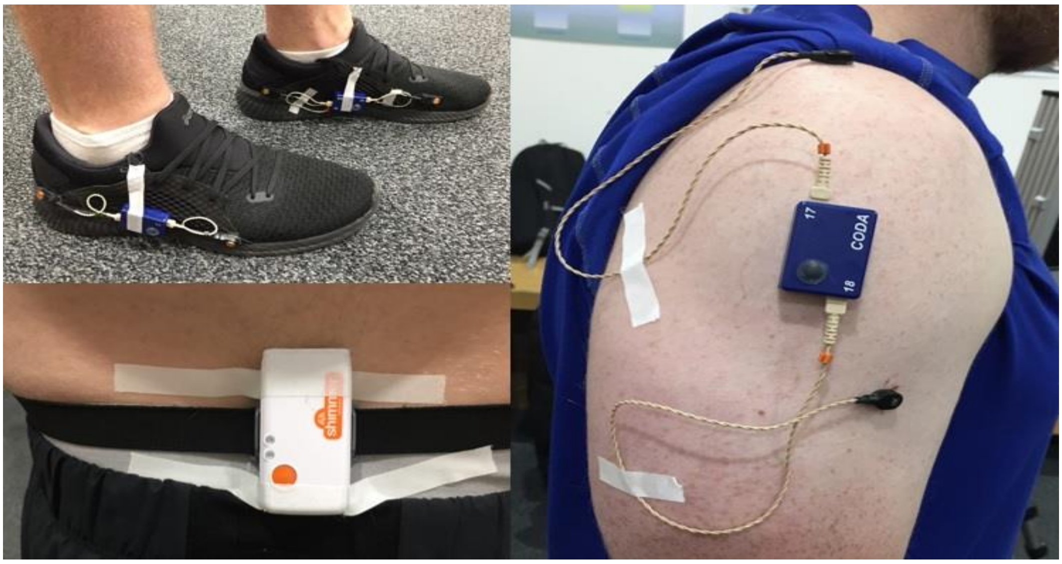

Figure 23 - T.L. Codamotion markers on the feet. B.L. Shimmer unit on the lower back. R. Codamotion markers on the shoulder

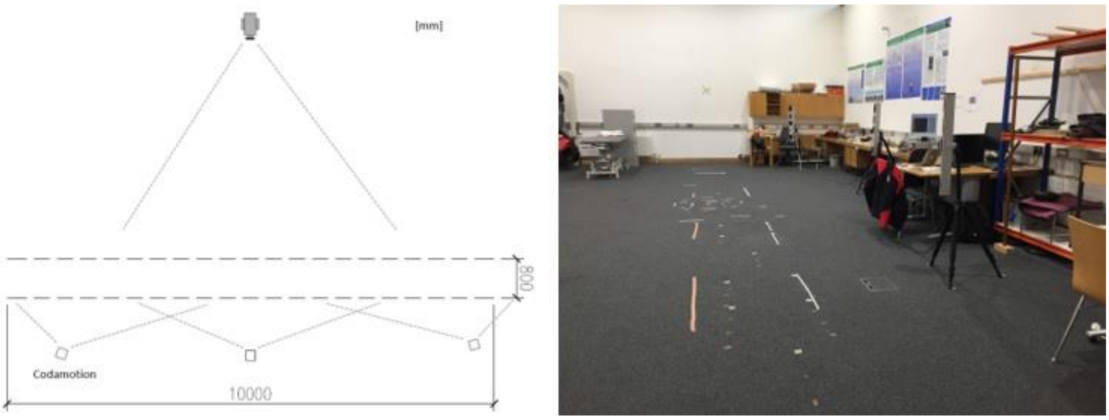

Figure 24 - L. Schematic of the set-up. R. Picture of the lab with the experiment prepared

4.2.4 Order of tests

Each experiment was divided into three parts. Part one was single file movement, part two was single file movement with a sudden stop, and part three was bunched together movement without overtaking. In order to control the speed at which participants were walking, one of the authors was leading the group, walking at or close to the desired speed. The speeds were derived from a review of different experimental studies, which can be found in Appendix B

In part one and two, the participants were told to follow the leader at a comfortable distance, while in part three they were told to walk close to each other as if they were in a narrow corridor. A total of 23 tests were performed with each group, divided into the three parts thusly:

- Part one - five different speeds, ten tests in total
- Part two - three different speeds, nine tests in total
- Part three - two different speeds, four tests in total

Table 5 shows the four experiment groups and the order of the tests, which was randomised, for each group. Each group is comprised of four participants, none of which attended more than one experiment. In order to interpret the table, the following example is given: if a test is named C3.4, it means that it is group C, part three and test number four.

Table 5 - Orders of tests for the motion capture experiments, with information regarding speed variations

Group A

Test	Speed [m/s]		
	Part one	Part two	Part three
1	0.5	0.5	1.0
2	0.2	1.0	0.5
3	1.3	1.3	1.0
4	1.7	0.5	0.2
5	1.0	0.5	0.5
6	0.2	1.0	-
7	1.3	1.0	-
8	1.0	1.3	-
9	1.7	1.3	-
10	0.5	-	-

Group B

Test	Speed [m/s]		
	Part one	Part two	Part three
1	0.5	1.0	1.0
2	0.2	0.5	0.2
3	1.0	0.5	1.0
4	1.3	1.0	0.2
5	0.2	1.3	-
6	1.7	1.0	-
7	1.7	1.3	-
8	1.0	1.3	-
9	0.5	0.5	-
10	1.3	-	-

Group C

Test	Speed [m/s]		
	Part one	Part two	Part three
1	0.2	1.0	1.0
2	1.7	1.3	0.2
3	1.3	0.5	1.0
4	0.5	1.3	0.2
5	0.2	0.5	-
6	1.7	1.3	-
7	1.0	1.0	-
8	0.5	0.5	-
9	1.3	1.0	-
10	1.0	-	-

Group D

Test	Speed [m/s]		
	Part one	Part two	Part three
1	0.2	1.3	1.0
2	1.3	0.5	0.2
3	1.7	1.0	1.0
4	1.3	1.3	0.2
5	0.5	1.0	-
6	0.2	0.5	-
7	0.5	1.0	-
8	1.7	0.5	-
9	1.0	1.3	-
10	1.0	-	-

4.2.5 Process of analysis

The motion capture system collects all the data automatically, compared to the video analysis process in section 0 where it was done manually. The sampling frequency at this automated process was 100 measurements/s. The tests chosen for analysis were B.1.9 and B.1.10. These were chosen to get one test at similar speed as analysed in the Lund experiment and one test with a "normal" walking speed. Looking at Table 5, this means that the tests are the 9th and 10th during part one of group B's experiment. A section of three meters was analysed in each test. There are a couple of assumptions made, one being that the marker on the shoulder assumes to be analogous to the hip marker during the experiment in Lund, Sweden, i.e. the inter person distance is measured between the shoulders instead of the hip. If the marker would have been on the hip, the obstruction caused by the pendulous motion of the arm during walking could have affected the results.

To conform to the analysis process in section 0, only the markers position in the direction of walking will be tracked i.e. the x-axis positions of the markers. In order to do this, an assumption has to be made since the markers were not placed on the toes' and the heel. Figure 25 is used to describe this assumption.

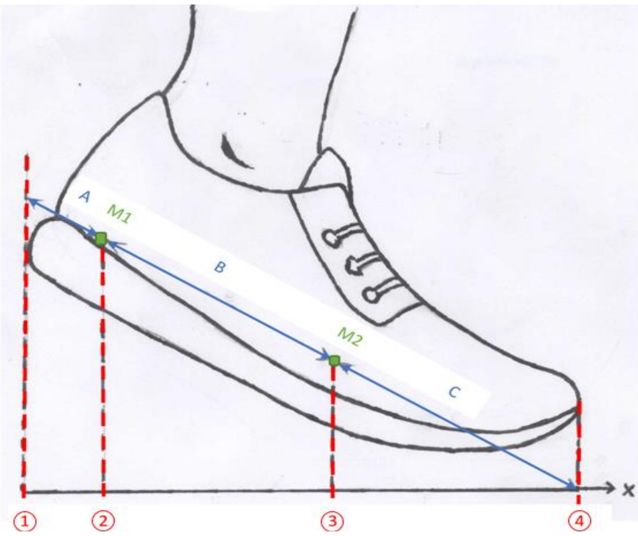

Figure 25 - The position of the heel and toe in relation to the markers, M1 and M2.

Codamotion gives the coordinates of the two markers M1 and M2. A proportion "P" between "B" and ②→③ is used to calculate the x-axis positons of the heel and toes' i.e. positions ① and ④. This proportion changes when the angle between the shoe and the floor changes. Any angle towards the y-axis, i.e. any foot rotation during a step, has not been considered.

The shoe length, or "ABC", along with the distance between M1 and M2, or "B", was measured prior to the tests, and M1 was always attached so that "A" was 0.03 m. The proportion "P" is determined by

$$P = \frac{③ - ②}{B}$$

The heel position, ①, is then calculated as

$$① = ② - (A * P)$$

Finally, the position of the toe, ④, is calculated as

$$④ = ① + (ABC * P)$$

Aside from this, the analysis and the development of the graphs were carried out in the same fashion as for the video capture experiment.

5 Results and comparison

In this chapter the results from the analysis are presented. Firstly, an introduction on how to interpret the results is presented, followed by the actual results. The results from the video capture experiment and the motion capture experiment are presented together in order to make it easier to compare them. They are presented in regard to inter person distance, step length and stride length, interaction between toe and heel, and contact distance. This is followed by the results from the eye tracker analysis.

It is important to consider that even though the analysis was performed on a limited amount of data, there is indeed considerable amounts of data collected. A goal of the thesis was to gather material that could be analysed further in the future. Figure 26 can be seen as a combination of Table 2 and Table 5, and it shows a review of the data collected, and which of the tests were analysed. As can be seen, the data from the inertial sensors was not further analysed. However, a review was performed to see if the data from the inertial sensors is useable and if any data was lost. This showed that no data was lost and that all data collected is usable for future analysis.

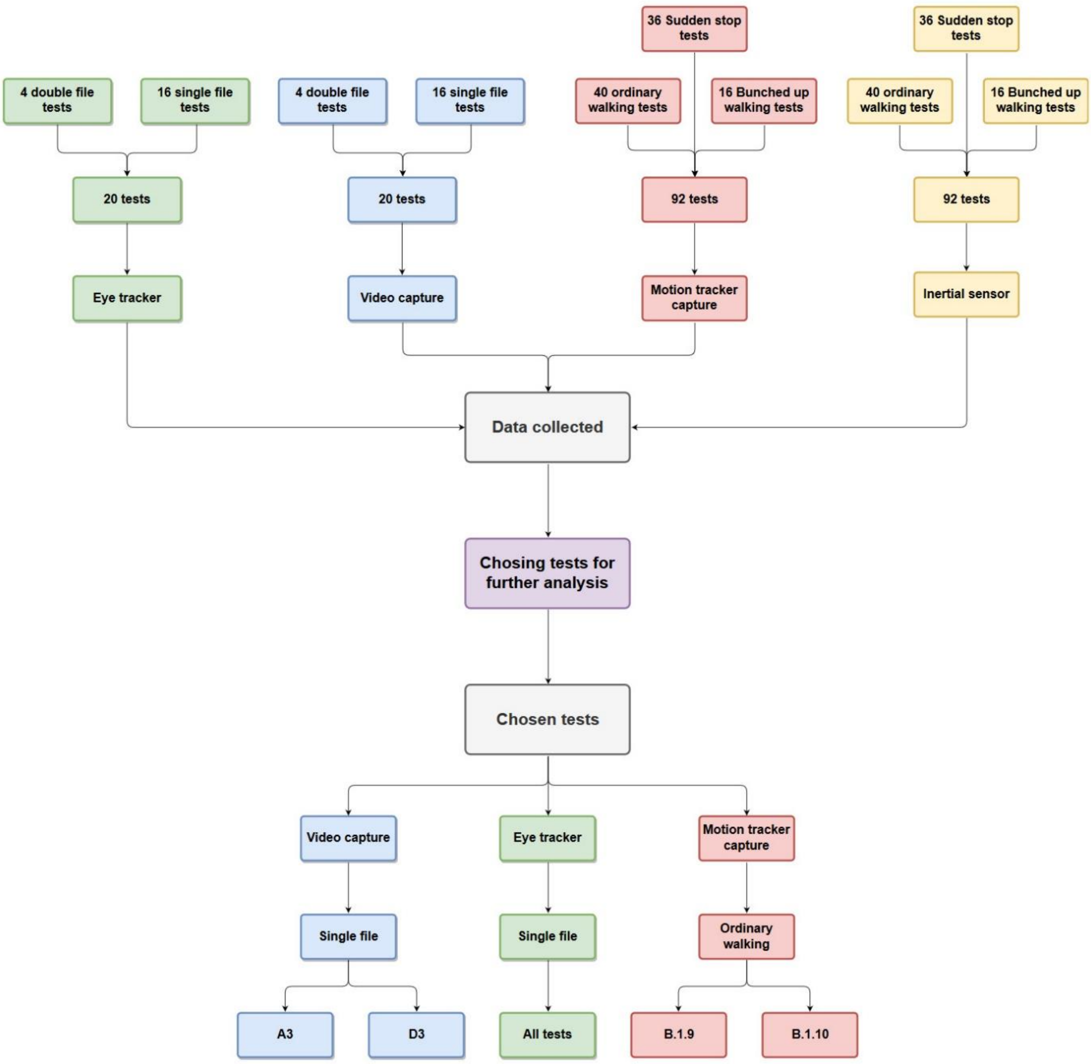

Figure 26 – Review of the collected data and which data was chosen for the analysis

5.1 Optical Methods

In order to compare the methods, the presented results are for tests D3 from the video capture experiment and for B1.9 from the motion capture experiment. During these tests the average walking speed was similar, 0.54 m/s and 0.47 m/s respectively. The other analysed tests, A3 from the video capture experiment and B1.10 from the motion capture experiment, had different walking speeds, but albeit not the same. A3 had a lower walking speed and B1.10 had a higher walking speed. The graphs relating to A3 and B1.10 are found in Appendix C. However, graphs regarding the interaction between the heel and toe will be presented for all four tests in the main report to illustrate how the speed affects the contact distance. Table 6 presents the tests in more detail, highlighting the tests that are presented in the main report.

Table 6 – Details regarding the analysed tests

Test	Aver. walking speed [m/s]	Pref. walking speed [m/s]	Person A height [m]	Person B height [m]	Sampling frequency [measurements/s]
A3	0.05	1.28	1.83	1.81	5
D3	0.54	1.23	1.80	1.83	8.33
B1.9	0.47	1.58	1.75	1.67	100
B1.10	1.33	1.58	1.75	1.67	100

The analysed area was four meters but only three meters are illustrated in the graphs. This is done to counter the persistent distortion problem described in section 0. In the motion capture experiment, the three receivers recorded data on an area approximately five meters long. However, only four meters are illustrated in the graphs in order to get a more detailed view.

5.1.1 Description of the graphs

The graphs in the following sections are presented in two different ways. One shows travel distance plotted against time, or absolute distance over time, while the other shows time plotted against a distance relative to a fictional, moving person in front of the group, or a relative distance over time. This fictional person travels with the average speed during the test, derived from the two analysed persons, which can be seen as an average reference speed vector. The colour scheme used, illustrated in Figure 27, is the same in both types of graphs. The person walking in front, or ahead, is illustrated with continuous lines while the person walking behind is represented by dotted lines.

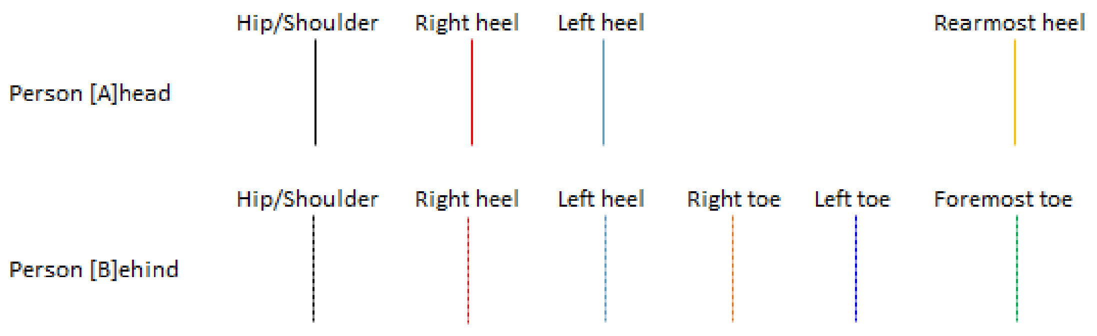

Figure 27 - The colour scheme used for the graphs

Regarding the rearmost heel and foremost toe, this is for the contact distance where the furthest point in front of "Person B" and the furthest point behind "Person A" are the ones that determine the contact distance. Figure 28 is presented as a recap of chapter 3 and shows how the inter person distance, step length and contact distance are measured. A note is that the step length a schematic illustration, it is measured from the heel strike of one foot to the heel strike of the other foot.

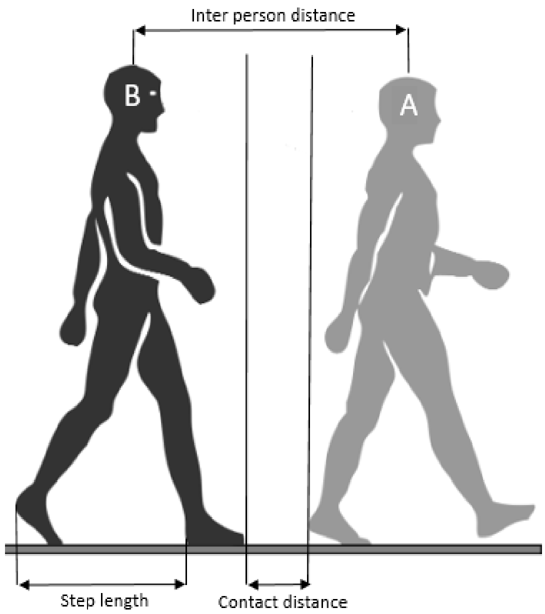

Figure 28 - Illustration of the measurements presented in the result

Figure 29 shows a schematic illustration of the absolute distance over time graph. It is presented to show the connection between this type of graph, and the relative distance over time graph. The two persons are walking at the same, constant speed in a direction which is represented by the vertical line on the left side of the graph. The lines representing the feet are showing a simplification of a step cycle. By looking at Figure 29, it is clear that black lines represent the hips, and the red lines represents the right heel. Since the walking direction is along the y-axis, the inter person distance between "Person A" and "Person B" is measured as the vertical distance between the two black lines. Subsequently, the distance between the heels is the vertical distance between the red lines. In the bottom right corner of the graph, the average speed of 0.5 m/s can be seen. This speed can be seen as the average reference speed vector. The steps in this graph are synchronized and the figure shows three strides each.

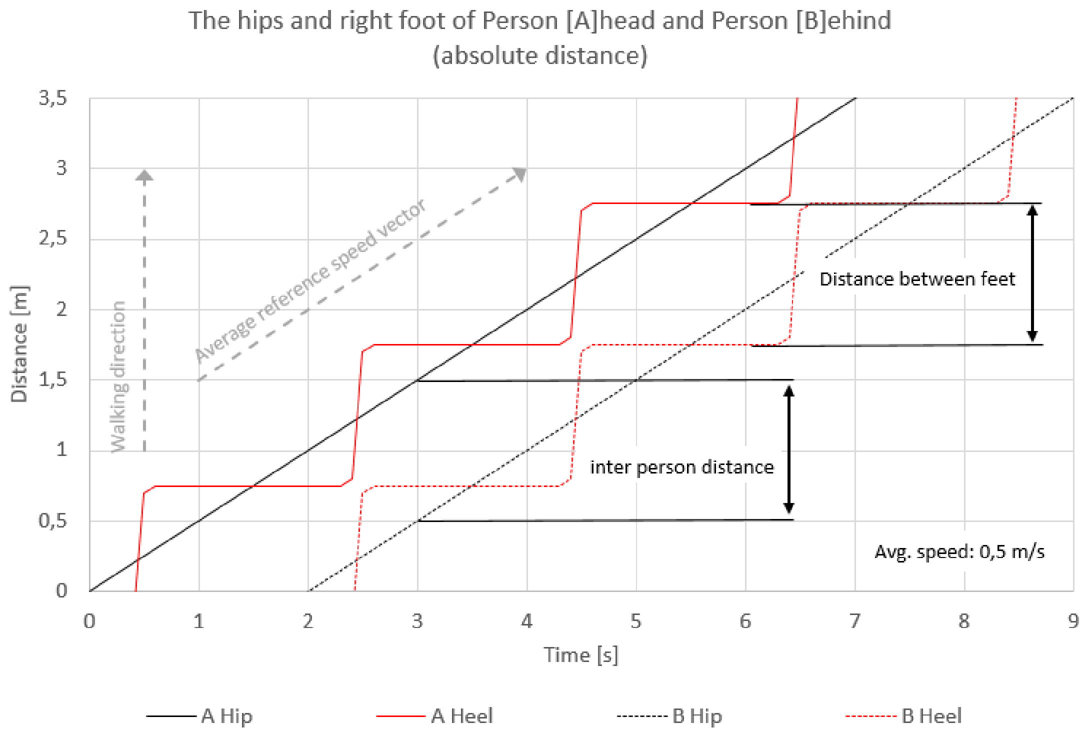

Figure 29 - Schematic illustration of the absolute distance of the hip and a foot of "Person A" and "Person B

The other type of graph, the relative distance over time graph, has to our knowledge not been presented before. Figure 30 is a schematic illustration, using the same raw data as in Figure 29. While looking at the graph, imagine two people walking on a treadmill being observed from above. The treadmill is moving with a constant speed that is equal to the average walking speed derived from the two persons, or the average reference speed vector. The inter person distance between the two persons is the horizontal distance between the black lines. The position of the hips is in relation to a fictional, moving person in front of the group, or the average reference speed vector, at each time step. The vector is plotted as a dotted grey line on the right side of the graph. Since the two persons are moving at the same, constant speed as the reference speed vector, the black lines are perfectly vertical. If they would have been walking at a faster, constant speed, the lines would have had a diagonal appearance, moving from the bottom left side of the graph, to the upper right. Subsequently, if they were walking at a lower, constant speed the lines would also have a diagonal appearance, but moving from the bottom right side of the graph, to the upper left. If the speed was not constant the lines would fluctuate more, alternating between being diagonal and vertical.

Figure 30 - Schematic illustration of the relative distance between "person A" and "Person B", and a moving person in front of group

This type of graph illustrates the gait cycle, and how the two step cycles interact with each other in a better way than the absolute distance over time graph. It is possible to see how the step cycle looks when “Person [B]ehind” is trying to avoid contact with “Person [A]head”. However, it is not possible to measure the step length and stride length directly from the graph without taking into consideration the distance travelled by the person, since the distance presented in the graph is a relative distance that changes each time step.

5.1.2 Inter person distance

In this section the graphs relating to inter person distance are presented, starting with the video capture experiment and ending with the motion capture experiment.

Video capture

In Figure 31, the hips of the two persons is plotted as time against distance. From these two lines it is possible to determine the inter person distance. The inter person distance at any specific time is the vertical distance between the two lines e.g. at 4 s the inter person distance is 0.88 m. The inter person distance varied between 0.77 m and 0.98 m, with an average inter person distance of 0.83 m. The density during this test was 1.41 ped/m and the average speed was 0.54 m/s.

Although this test was chosen as an example of laminar flow, there are some indications of stop-and-go waves. These can be seen at approximately 1.5, 3 and 4.5 s for "Person A", with a small offset in time for "Person B". The average walking speed of these two persons, 0.52 m/s, is plotted as the average reference speed vector.

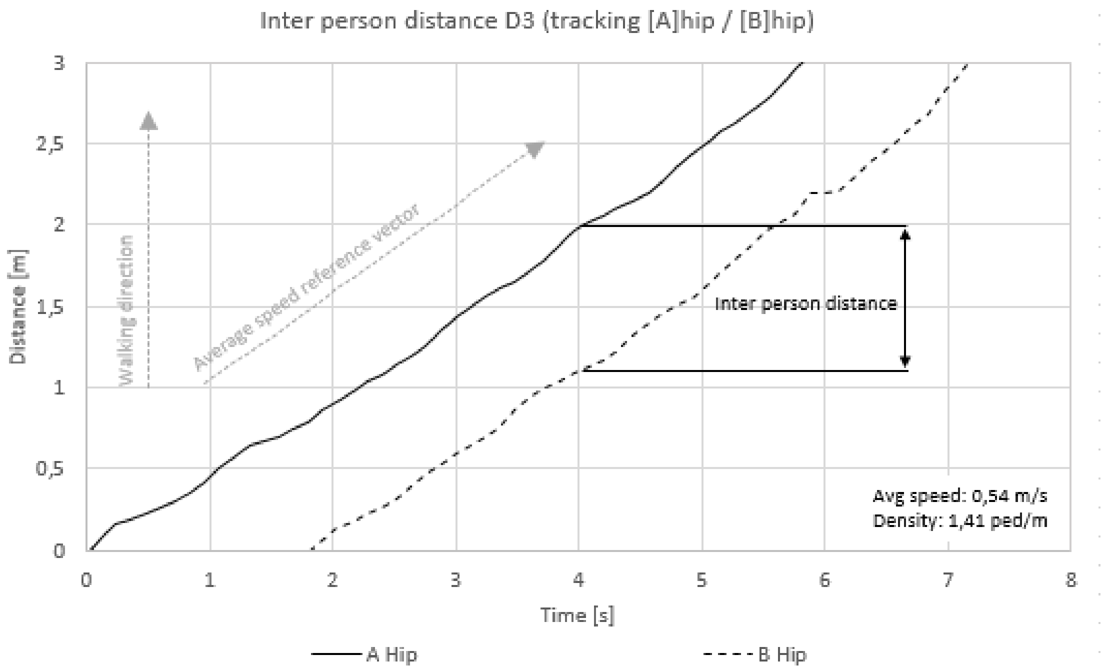

Figure 31 - Inter person distance for test D3 from the video capture experiment

In Figure 32 the relative distance graph of the graph in Figure 31 is presented, where the time is plotted against the relative distance to the fictional, moving person in front of the group, moving at the average speed derived from the two persons. The hip trace shows how each person's speed varies in relation to this fictional person. The horizontal distance between the two hip traces is the inter person distance. Again, at 4 s the inter person distance is 0.88 m. In this graph, the walking direction is indicated by the horizontal arrow at the top of the graph.

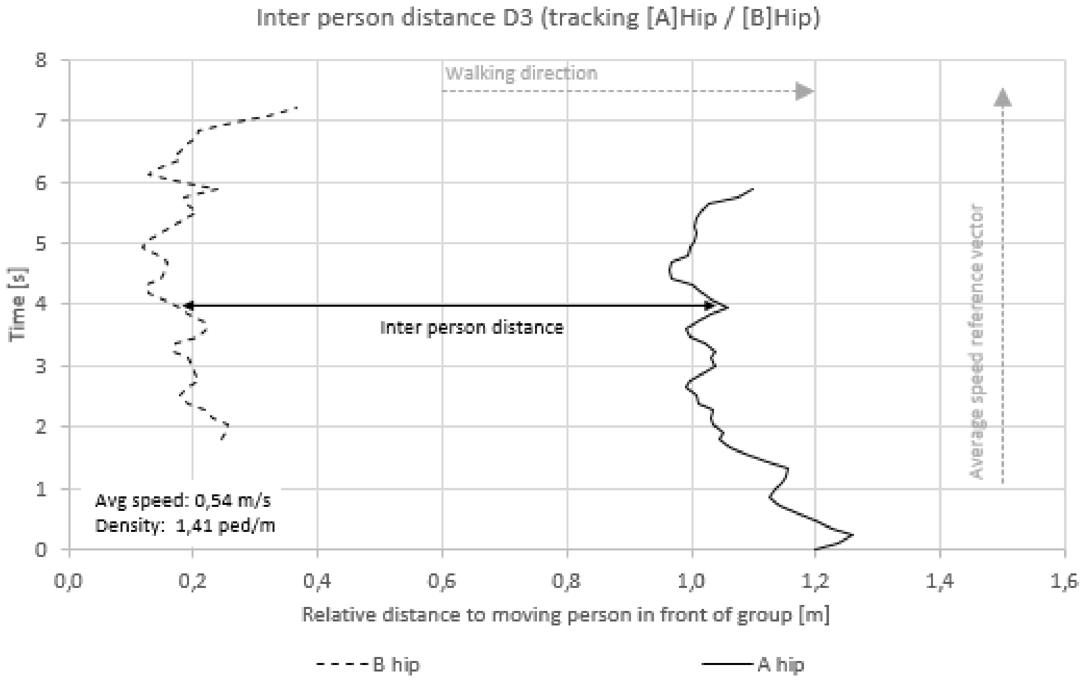

Figure 32 - Inter person distance for test D3 from the video capture experiment, presented as a relative distance

Motion capture

The average walking speed during this test was 0.47 m/s and the inter person distance varied between 0.74 m and 0.96 m, resulting in an average value of 0.83 m. Note that this is the same value as for the test from the video capture experiment.

In Figure 33, the inter person distance is 0.77 m at 4 seconds. It is also evident that the flow is almost laminar, with some smaller tendencies of stop-and-go waves for “Person A” at 2.5 s, 4 s and 5.5 s. Regarding “Person B”, these tendencies are almost non-existent.

Figure 33 - Inter person distance for test B1.9 from the motion capture experiment

In Figure 34, the inter person distance at 4 s is, again, 0.77 m. “Person A” seems to vary his or her speed more often than “Person B”. Note that the lines in this chart is smoother than in Figure 32. This difference is explained by the fact that the sampling frequency was higher for the motion capture experiment.

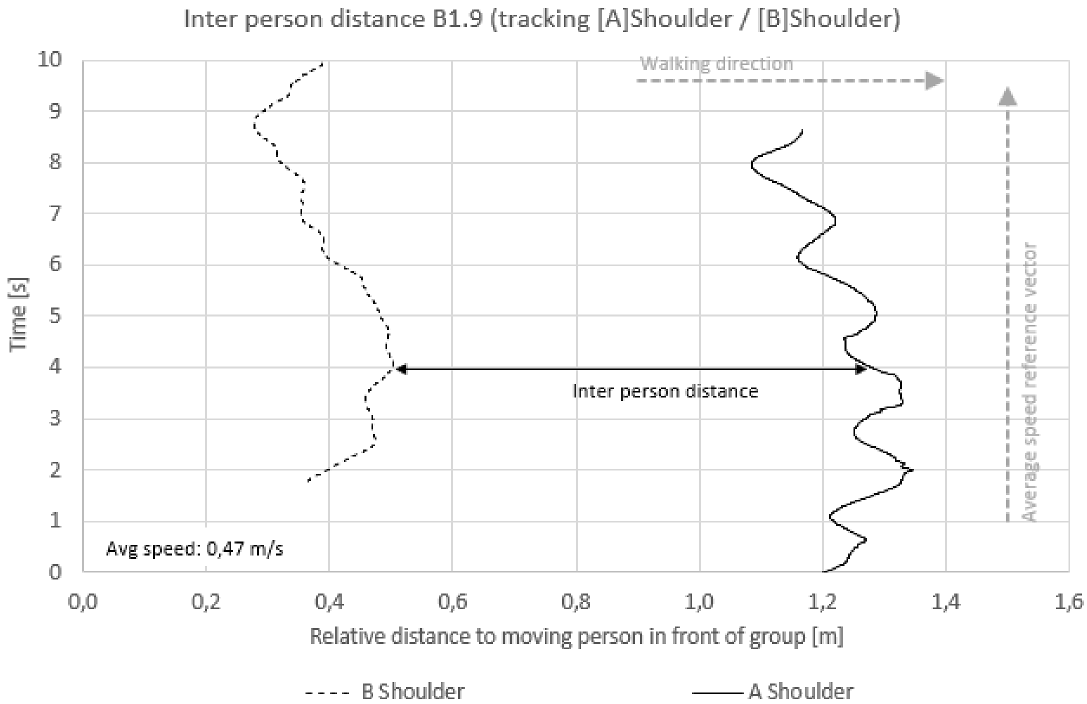

Figure 34 - Inter person distance for test B1.9 from the motion capture experiment, presented as a relative distance

The result from these four figures show that the average inter person distance is the same for the two experiments, even though the set-up was different. The two persons do not have the same speed during the section measured and the flow is almost laminar.

5.1.3 Step length & Stride length

In this section, graphs relating to step and stride length are presented. This section only includes the absolute distance charts and the reason for not including the relative distance charts is that the distances are relative to a moving, fictional person and it is not possible to measure distances at different times. The step length and stride length are measured from the position at one time step to the position at another time step. To do this in the relative distance charts, the distance travelled has to be accounted for as well.

Video analysis

By adding the data points from the heels of “Person A” and “Person B” to Figure 31 presented above, the step and stride lengths can be observed. This is shown Figure 35 where the average step and stride lengths were 0.47 m and 0.94 m respectively. There are three strides and six steps each for “Person A” and “Person B” and the average step and stride time was 0.9 s and 1.81 s respectively. The steps are almost syncronized between the two persons, but it can be seen that “Person B” has a delay of approximately 0.2–0.3 s.

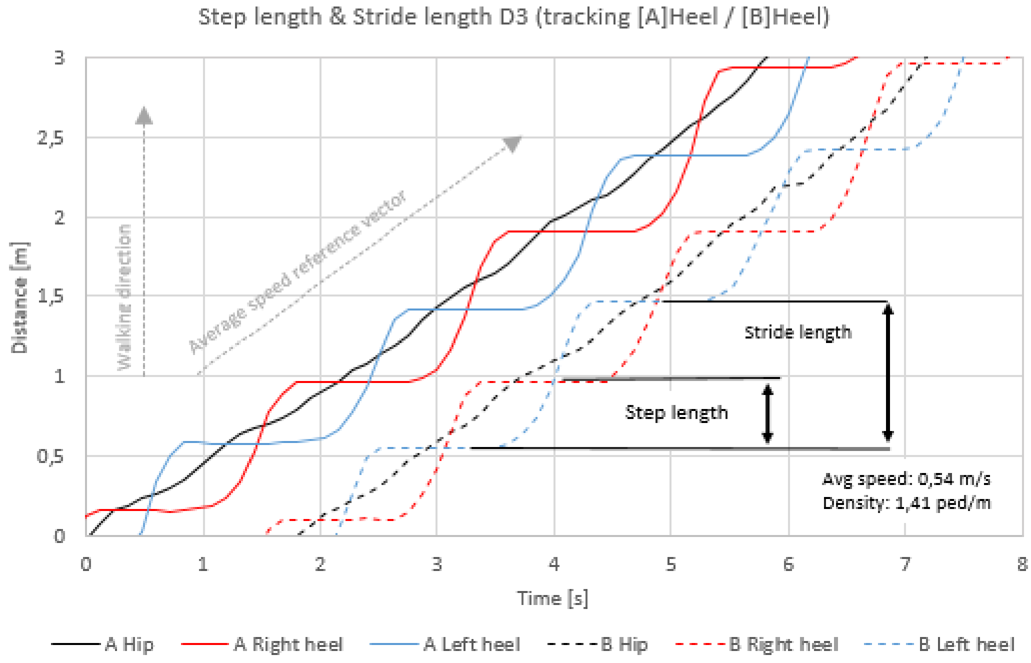

Figure 35 - Step length and stride length for test D3 from the video capture experiment

Motion capture

In Figure 36, the heels of “Person A” and the heels of “Person B” have been added to Figure 33. The average step and stride lengths were 0.38 m and 0.76 m respectively, while the average step and stride time is 0.87 s and 1.74 s respectively. The steps lengths are smaller in this test compared to the video capture experiment. There is also a difference in the average walking speed, which affects the step length. The difference in step time between the two tests is 0.06 s.

The steps are not synchronized in this test, but the right foot of “Person A” is moving forward at approximately the same time as the left foot of “Person B”. Note the heel of “Person B” between approximately 2.3 and 3.3 s, this difference in appearance is most likely explained by an issue with either the sensors or the marker, but exactly what happened at that time is unclear. Also, note the circumscribed area of the graph, this shown an example where a marker is temporarily obstructed, producing values that appear slightly erratic.

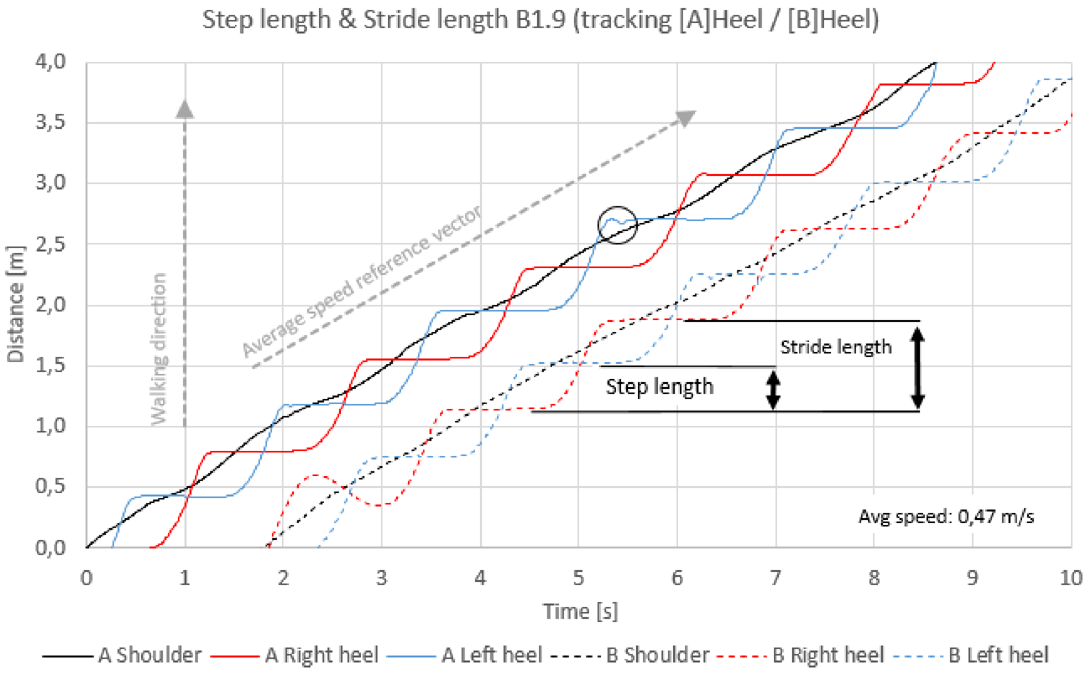

Figure 36 - Step length and stride length for test B1.9 from the motion capture experiment.

Although the average inter person distance was the same in the two experiments, the step and stride length were not the same. The difference was 0.09 m with the step length being longer in video capture experiment.

5.1.4 Interaction between heels and toes

In this section, graphs relating to the interaction between toes and heels are presented. What is different from the other sections is that the absolute distance-graphs for test A3 from the video capture experiment and test B1.10 from the motion capture experiment is presented here as well, in addition to the regular results from test D3 and B1.9. This is done to show that the distance between two persons differ at different speeds, meaning the contact distance is different as well. However, the results from A3 and B1.10 will only be presented using the absolute-distance graphs. The results from A3 will be presented first, followed by the usual comparison of D3 and B1.9, and lastly B1.10.

Video analysis

To see if any overlapping of the step cycles occurs i.e. if the toes of the person behind goes past the heels of the person in front, and how the feet interact with each other, the heels of "Person A" and toes of "Person B" are plotted together with the hip values. Figure 37 illustrates this for test A3. The average inter person distance is 0.29 m at the speed of 0.05 m/s. It can be seen that the distance between the heels of "Person A" and toes of "Person B" is very low, the average distance being negative, -0.02 m.

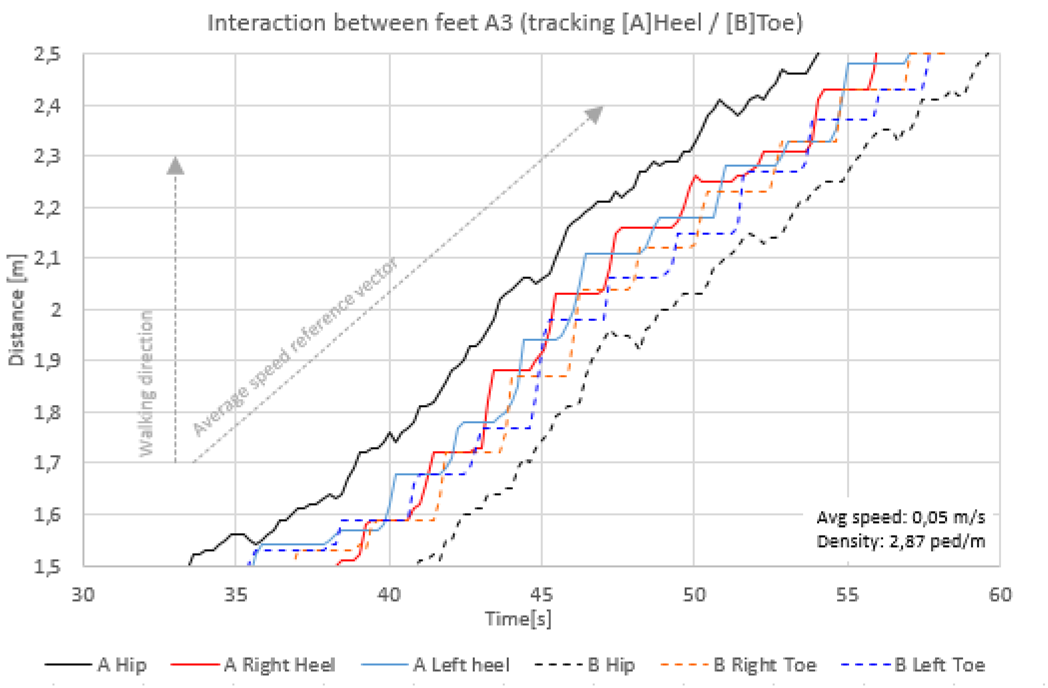

Figure 37 - The interaction between heels and toes for test A3 from the video capture experiment

This can be compared to the test D3, where the speed was around ten times higher (0.54 m/s). All distances i.e. the step length, inter person distance as well as the contact distance, are larger at this speed and no overlapping occurs as Figure 38 shows. However, overlapping almost occurs at a few occasions, e.g. at 6 s where the distance is 0.08 m.

Continuing with the comparison at the 4 second mark, the distance between their feet at that time is 0.33 m.

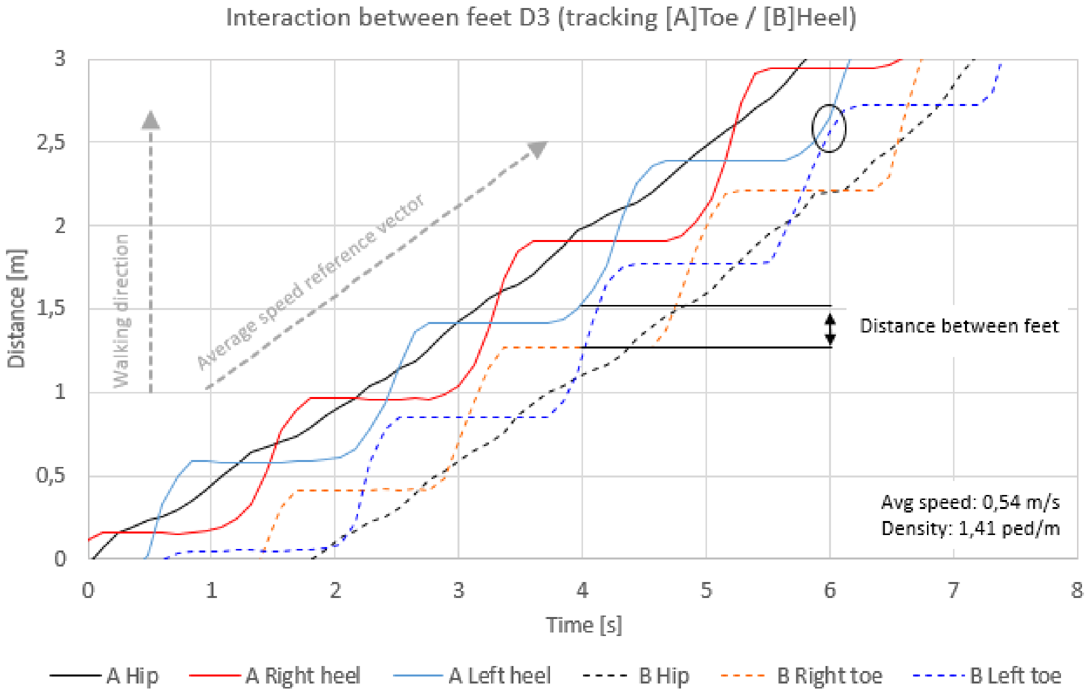

Figure 38 - The interaction between heels and toes for test D3 from the video capture experiment

The relative distance graphs are better at illustrating the interaction between the heels and toes, as can be seen in Figure 39. The horizontal distance at each time step visualises how close the toes of "Person B" are to overlap the heel of "Person A". Taking the horizontal distance from maximum extent on the left-hand side of a hip trace to the hip trace gives the backwards step extent, and the horizontal distance from the hip to the maximum extent on the right hand side of the same hip trace gives the forward step extent. Combining these two gives the total step extent.

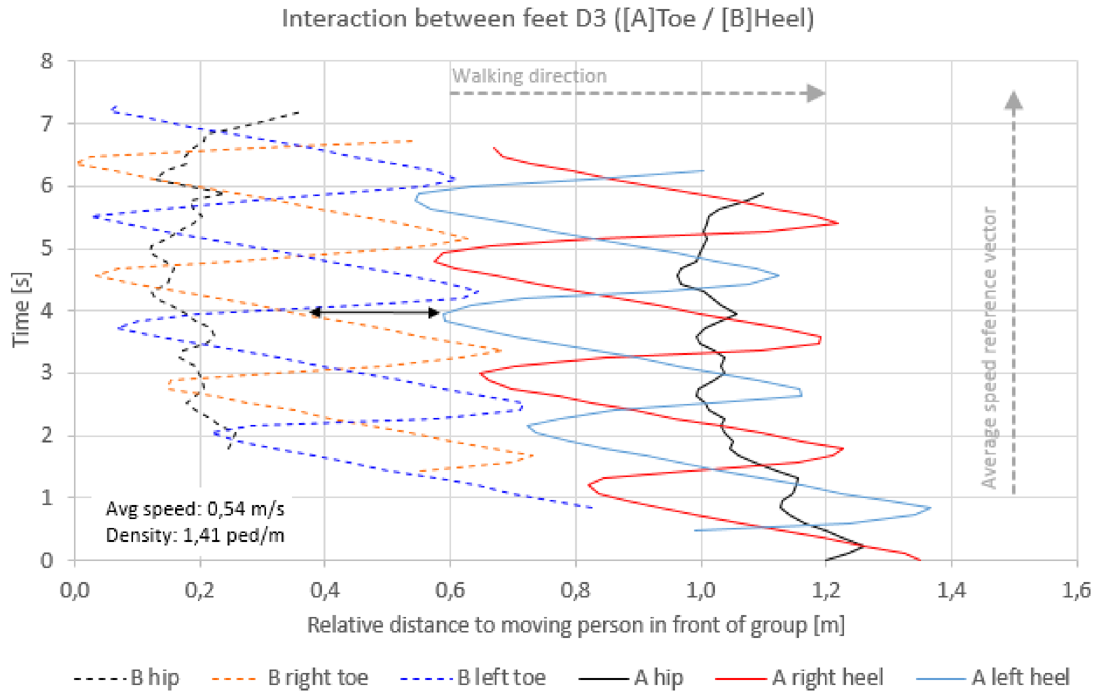

Figure 39 - The interaction between heels and toes for test D3 from the video capture experiment, presented as a relative distance

The amplitudes are wider at the end of the measured path than near the beginning, which can be explained in two ways. Firstly, it is because the participants sped up during the test which lead to an increase in step length. Secondly, "Person A" is walking closer to the video camera at the end of the analysed area than at the beginning, while "Person B" only walks in the middle of the analysed area, as can be seen in Figure 40. This mainly affect the results for "Person A"

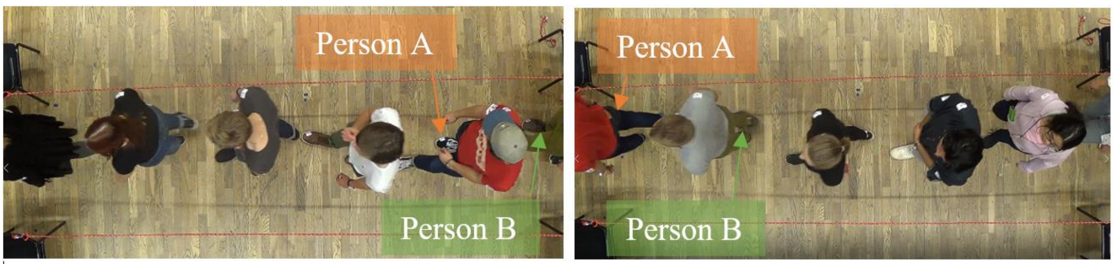

Figure 40 - Person A and Person B in the beginning and the end of the analysed area

"Person B" is in some way planning where to put and when to move his or her feet in order to avoid contact with "Person A", while still maximising the step length given the space available. There is a delay of approximately 0.2–0.3 s from the toe-off of "Person A" to the heel strike of "Person B".

There was no overlapping of the step cycles in this experiment either. Figure 41 shows that the distance between the feet was larger in this test compared to the previous one. At 4 seconds the distance between the right feet is 0.22 m and between the left feet the distance is 0.89 m. The speed at this test is a little bit lower than the other and then it is quite expected that the step length is smaller which in turn gives more space between the persons. This will be illustrated in the graphs in the next section.

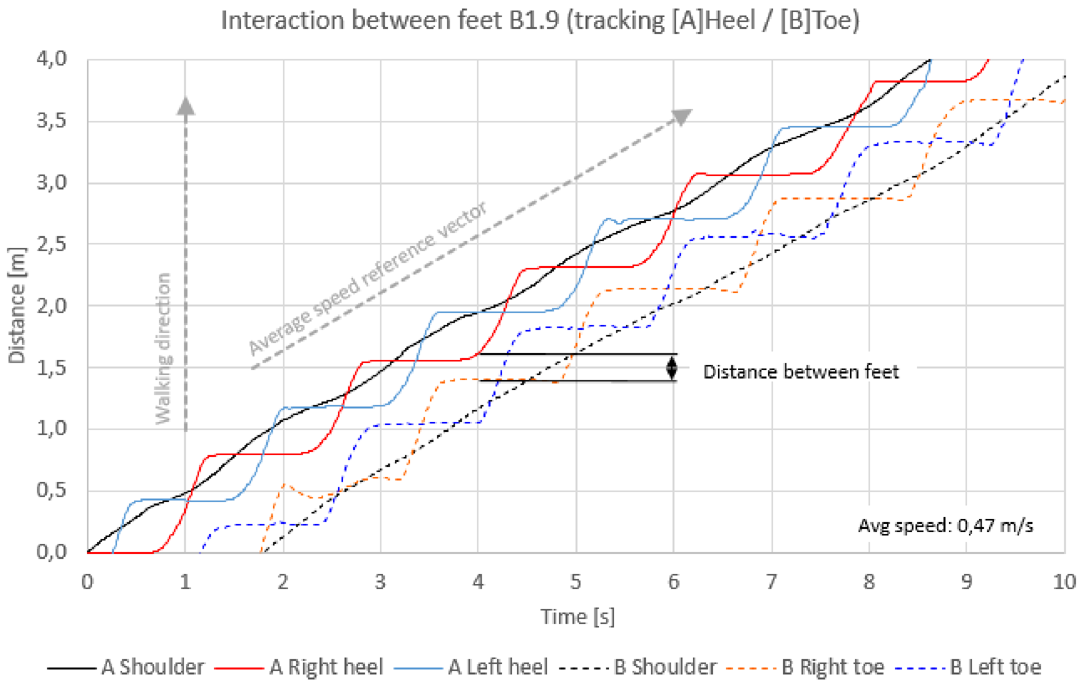

Figure 41 - The interaction between heels and toes for test B1.9 from the motion capture experiment

As described earlier, there are some differences in appearances in the graph which can be seen between the 2 and 3 second marks. The differences are explained in the same way as for Figure 36, that there probably was an issue with either the sensors or the marker.

Figure 42 shows the gap between the two persons more easily compared to the absolute distance graph. This becomes even clearer while looking at the graphs relating to contact distance in the upcoming section. The horizontal distance at 4 seconds is the same as for the other chart, 0.22 m between the right feet and 0.89 m between the left feet.

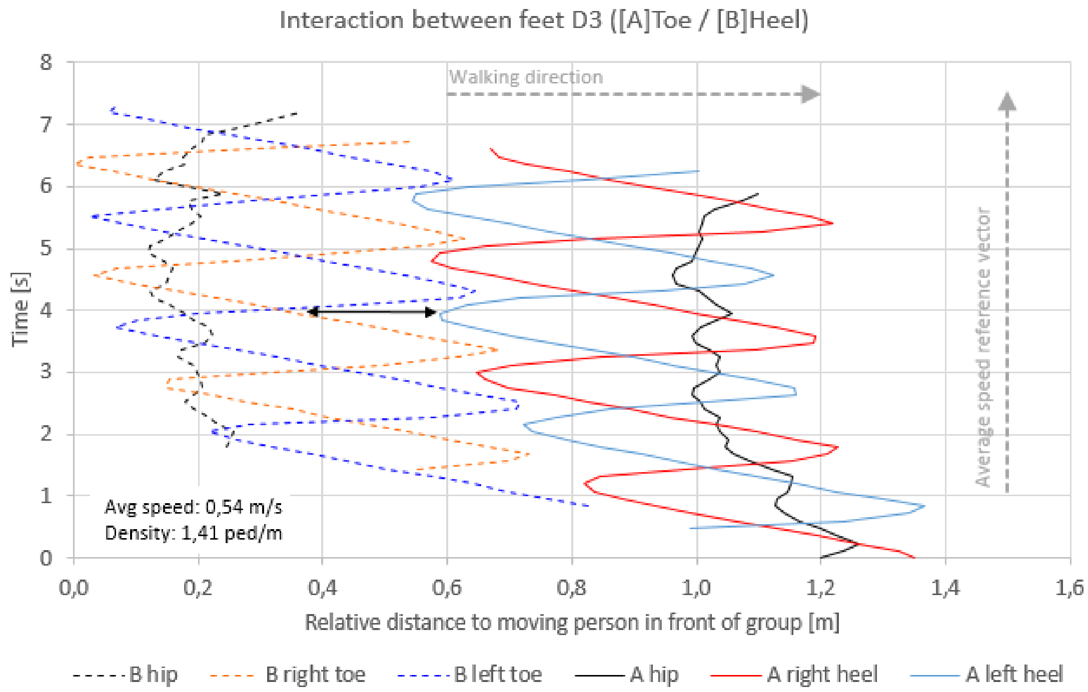

Figure 42 - The interaction between heels and toes for test B1.9 from the motion capture experiment, presented as a relative distance

In Figure 43 the test B1.10 is shown. The speed is 1.35 m/s which, in this case, gives an inter person distance of 0.96 m and a contact distance of 0.38 m. No overlapping can be seen here either, even though the step length is longer than for the other tests.

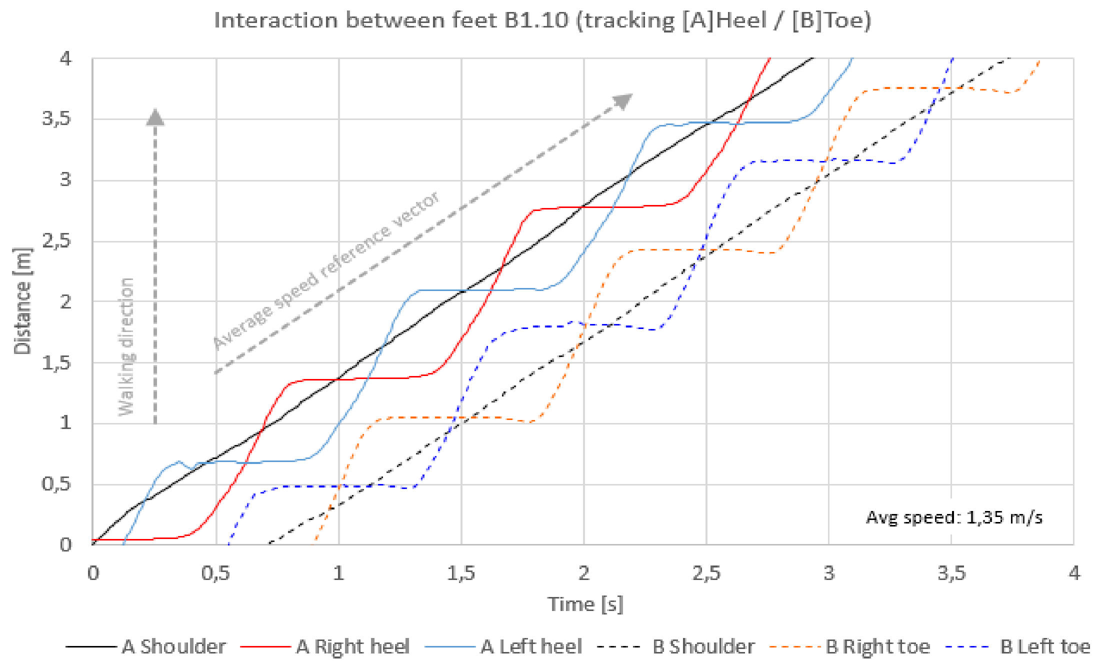

Figure 43 - The interaction between heels and toes for test B1.10 from the motion capture experiment

5.1.5 Contact distance

In order to obtain a measurement of the contact distance, the rearmost heel of "Person A" and the foremost toe of "Person B" is plotted. These values are derived from Figure 38 and Figure 41, essentially merging the right and left heel positions of "Person A" and the right and left toe of "Person B", to obtain a single-trace "nearest contact" line for each person. This is illustrated before, in Figure 28 in section 5.1.1.

In the video capture experiment, the positions of the posterior and anterior were tracked. This was to see if these affect the contact distance. In some time step these body parts did but that was only in the test A3 where the back of "Person A" often is the body part closest to "Person B" but the toes always gave the furthest point in front. Since no measurements were taken for the posterior and anterior in the motion capture experiment, only the rearmost heel and the foremost toe is plotted. But it is important to note that, at high densities and low speeds, the posterior is a determining factor when measuring the minimum distance to the person behind.

Video analysis

Figure 44 shows the rearmost heel and front most toe values, describing the change in contact distance over time. Note, the hip traces are useful reference points when measuring this. At 4 seconds, the contact distance is 0.2 m, while the distance varies between 0.08 m and 0.43 m during the entire test. This gives an average contact distance of 0.17 m.

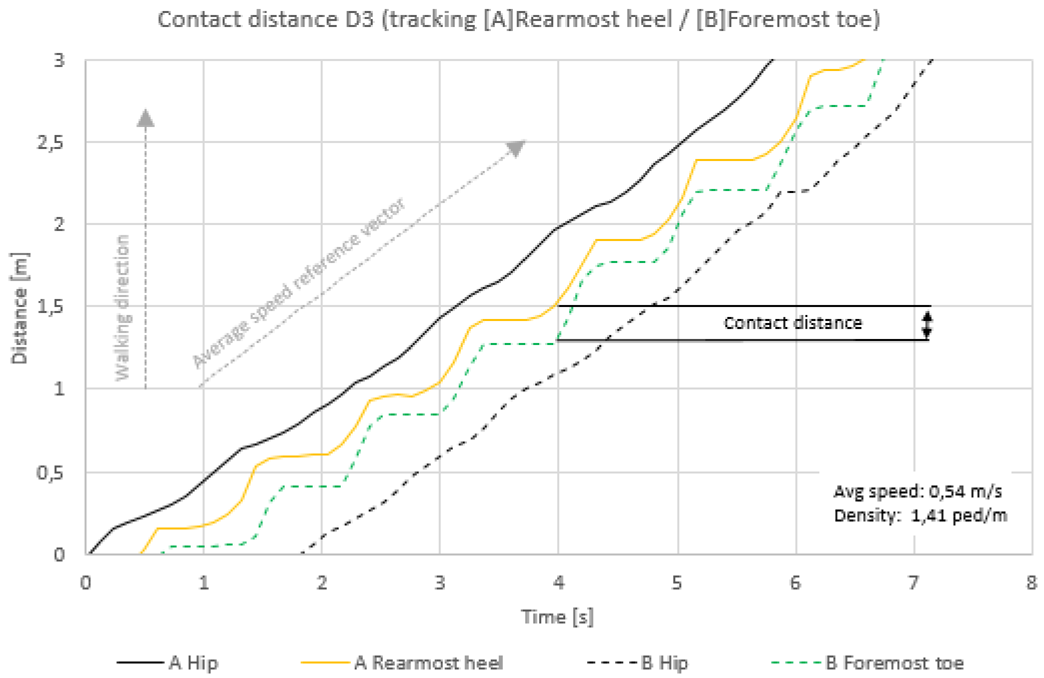

Figure 44 - The contact distance for test D3 from the video capture experiment

While Figure 39 shows the interaction between the feet, as well as the step cycles, Figure 45 clearly illustrates the contact distance at any point in time. The available space between “Person A” and “Person B” is the area between the yellow and the green lines.

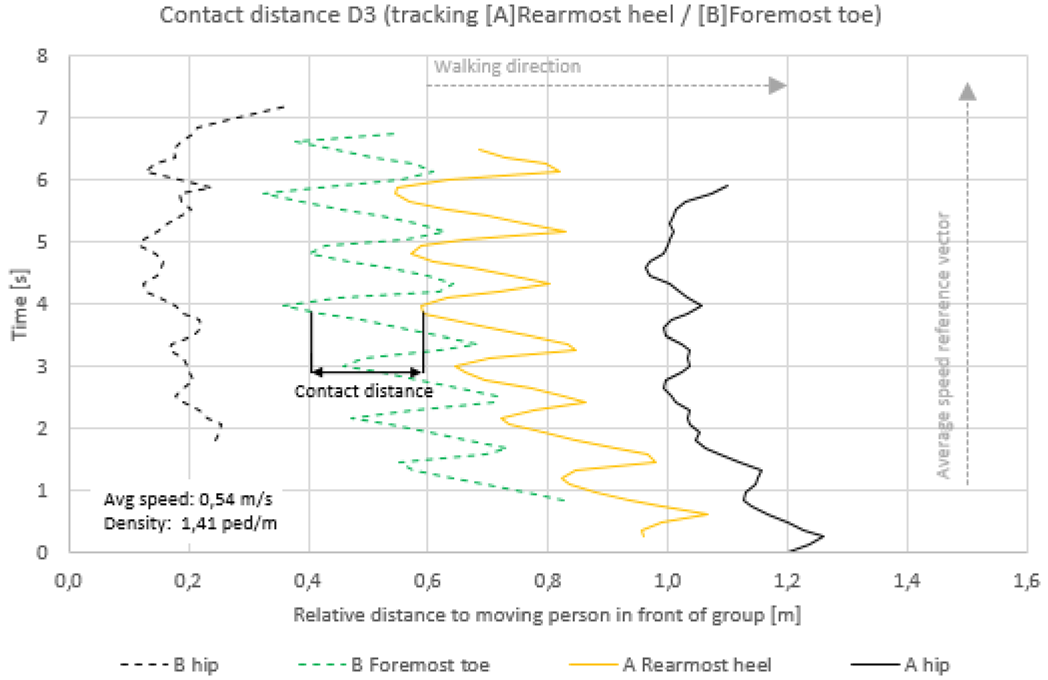

Figure 45 - The contact distance for test D3 from the video capture experiment, presented as a relative distance

Figure 46 illustrate how the contact distance varies between 0.08 m and 0.43 m during the test. Note that the sampling frequency has affected the resolution of the chart which affect the peaks and troughs, giving them a “sharper” look.

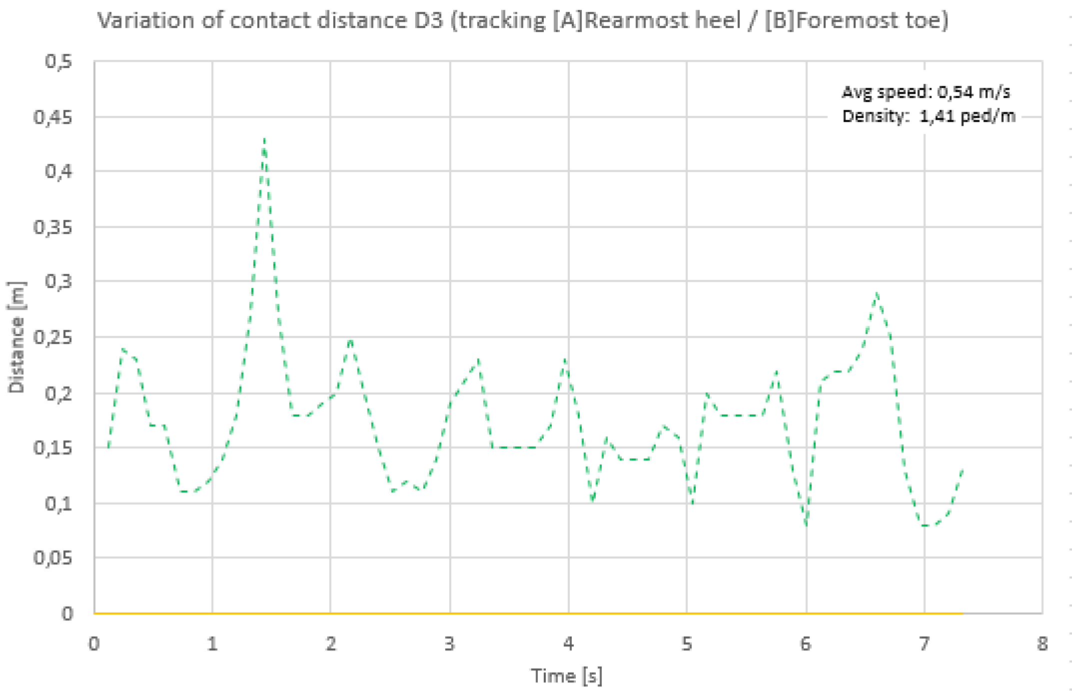

Figure 46 - Variations of contact distance for test D3 from the video capture experiment

Motion capture

In Figure 47, the rearmost heel of "Person A" and the foremost toe of "Person B" is plotted to describe the changing of contact distance over time. At the 4 second mark, the contact distance is 0.21 m. The average contact distance in this test was 0.27 m. The green line displays a trough at 2.0–2.5 s, which is in the same area where differences in appearances where found in Figure 36 and Figure 41. The contact distance is larger during this time step as a result of this.

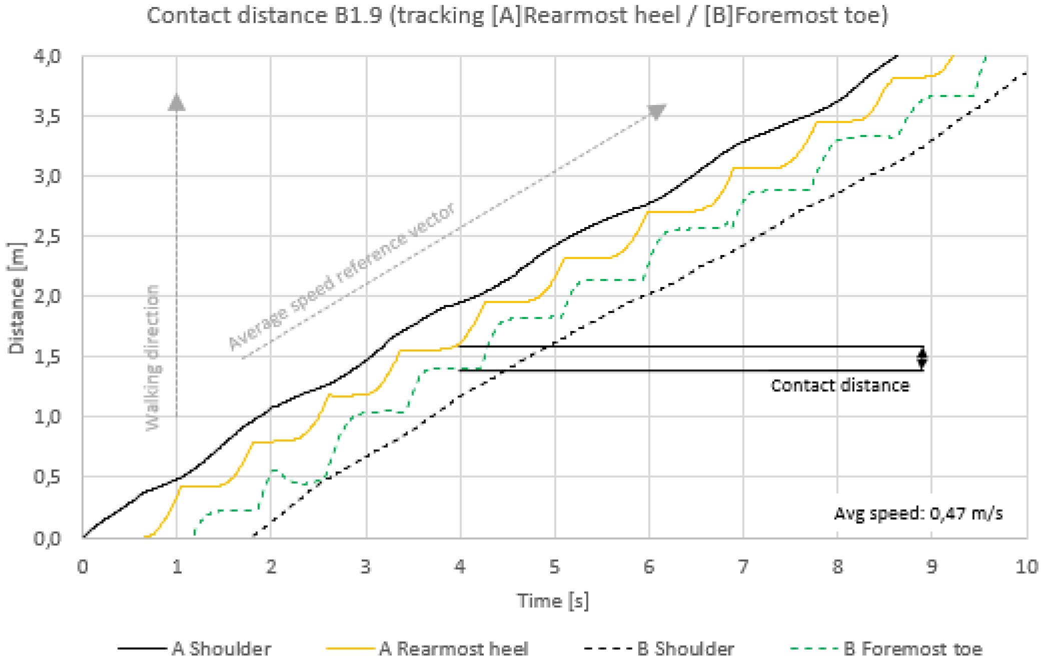

Figure 47 - The contact distance for test B1.9 from the motion capture experiment

The contact distance at any point in time is also illustrated in Figure 48, where the increase in contact distance due to the trough is easily spotted. The space between the persons is larger in this figure than in Figure 45 even if the speed is slower and the steps are smaller.

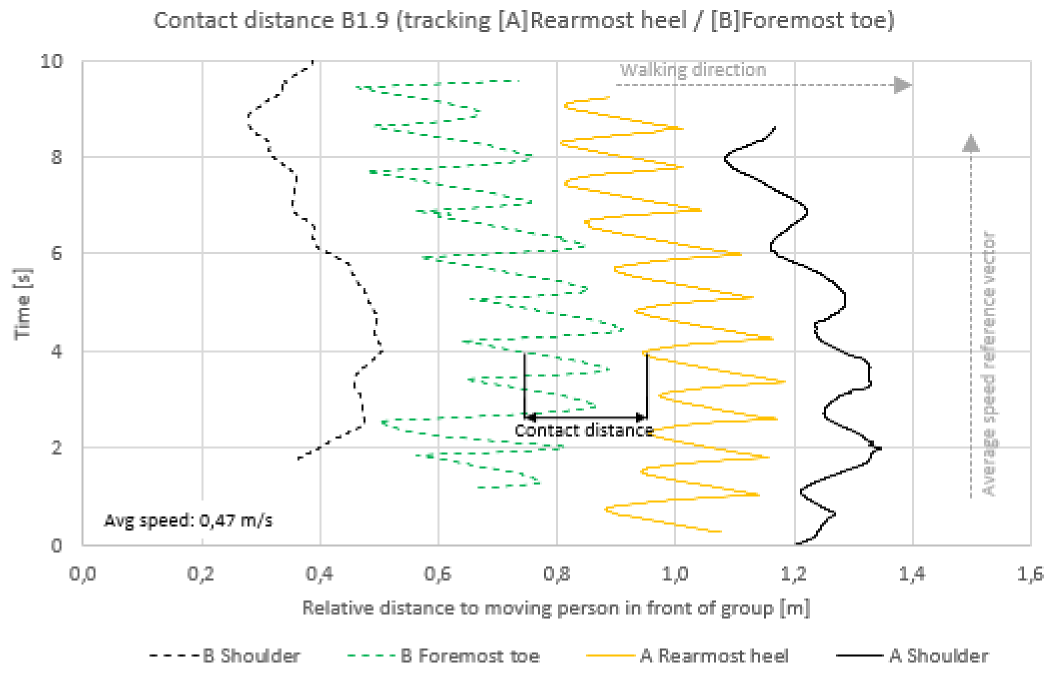

Figure 48 - The contact distance for test B1.93 from the motion capture experiment, presented as a relative distance

As Figure 49 shows, the contact distance varies between 0.13 m and 0.61 m. The peaks and troughs in this experiment have a smoother appearance due to the higher sampling rate compared to the video capture experiment.

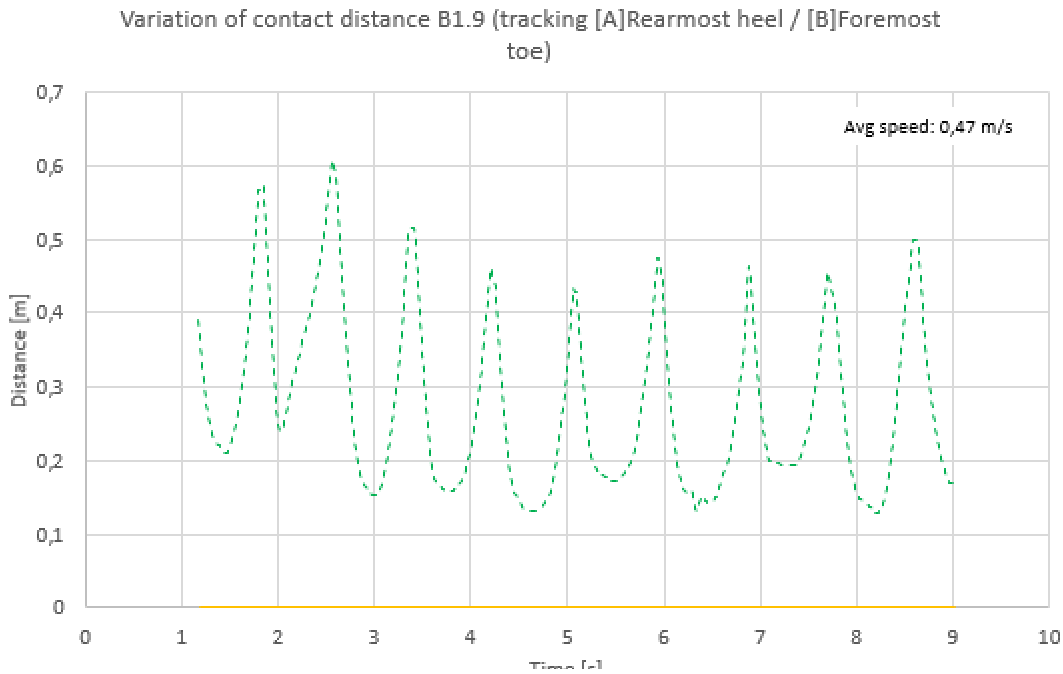

Figure 49 - Variations of contact distance for test B1.9 from the motion capture experiment

5.1.6 Relationship between walking speed and distance parameters

A summary of the results from the four tests are presented in Table 7. As previously mentioned, the graphs for A3 and B1.10 can be found in Appendix C.

Table 7 - Summary of the results from the four analysed tests

Test	Average walking speed [m/s]	Average inter person distance [m]	Average step length [m]	Average stride length [m]	Average contact distance [m]
A3	0.05	0.29	0.06	0.12	-0.02
B1.9	0.47	0.83	0.38	0.76	0.27
D3	0.54	0.83	0.47	0.94	0.17
B1.10	1.35	0.96	0.38	0.77	0.38

Figure 50 - Trends for inter person distance, step length and contact distance, in relation to walking speed shows a possible connection between the contact distances, inter person distance and step length in relation to the walking speed, derived from the data in Table 7. A trend line has been added for each of the three parameters, and the gradient for step length and inter person distance is practically the same, 0.4467 s (m/(m/s)) and 0.4466 s respectively. The relationship is linear plotted due to the limited amount of analysed data points. The coefficient of determination, or R^2, is 0.6630 for the inter person distance and 0,8861 for the step length. The contact distance does not share this linear relationship, but it increases linearly with speed and can therefore be expressed as a time, which gives the contact buffer of approximately 0.28 s, which also is the contact distance gradient. The coefficient of determination for the contact distance is 0,8066.

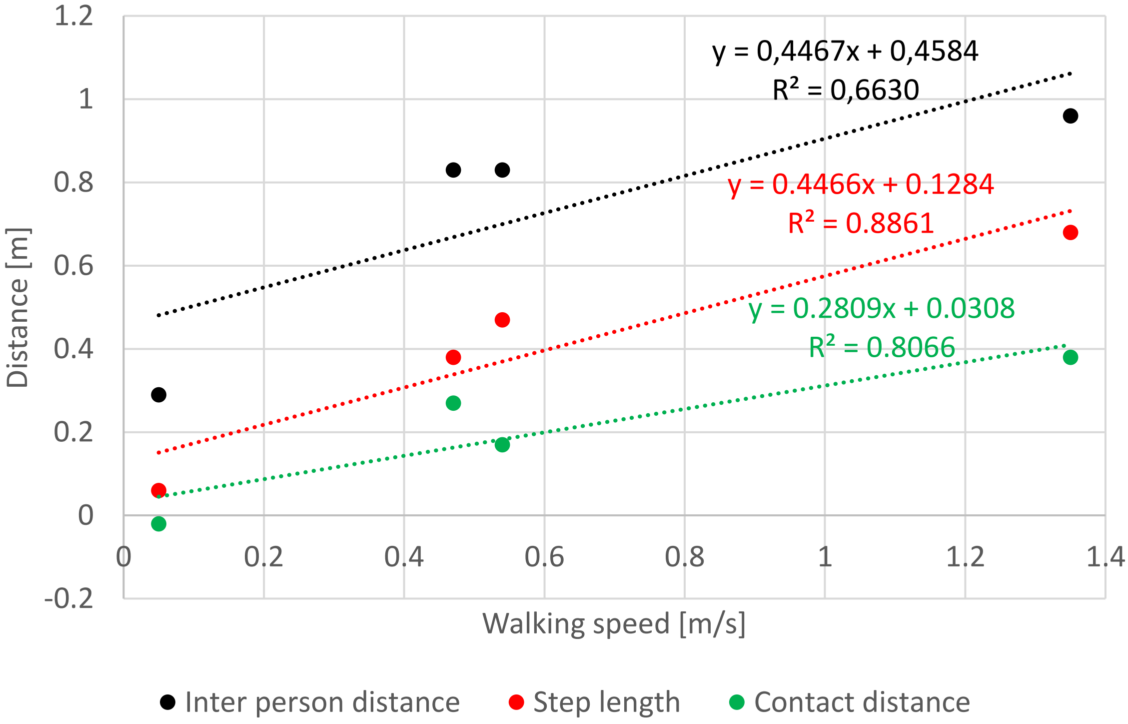

Figure 50 - Trends for inter person distance, step length and contact distance, in relation to walking speed

In Figure 50, the difference between step length and inter person distance at near-zero speed is about 0.3 m, This is approximately the size of the average shoe length, derived from the analysed participants, which was 0.297 m. Figure 51 shows that the average shoe length "d_2" is similar to the average body depth "d_1", which is the "missing component" of inter person distance. It seems that contact distance and step length together with the foot length gives the inter person distance. But also note that at lower speeds and with bigger persons the depth of the body may be the determining factor for the contact distance instead of the foot.

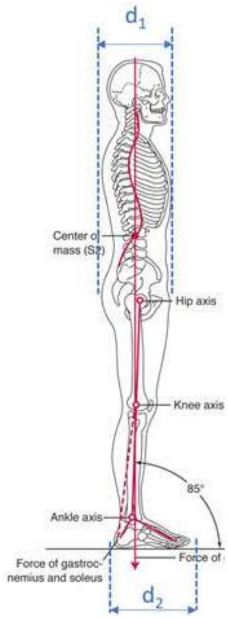

Figure 51 – Relationship between body depth and shoe length.

5.2 Eye tracker

This section will present the results from the analysis of the eye tracker data.

5.2.1 Description of the graphs and pictures

The graphs presented in this section are both pattern and colour coded, Figure 52 clarifies the colour and pattern scheme. As an example, if the back of person 3 is included in the graph, it would be purple in colour with a horizontally-striped pattern. Showing all categories would make the graphs incomprehensible since there are three persons and seven categories per person. The "All Other Areas" category is a combination of one or more categories that make up less than 1% of the total data points in the graph, i.e. if the total data points are 200 while "Person 1 Back" and "Person 3 Shoulders" have 1 data point respectively, they will be added to the "All Other Areas" category. If a category has no data points at all, it is excluded entirely.

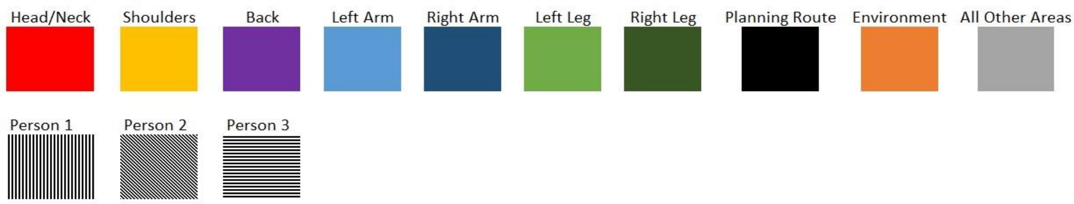

Figure 52 - Colour- and pattern scheme for the graphs regarding eye tracker

During the experiment the eye tracker was worn by different participants and the order of the people standing in front of the users varied, as shown in Table 2. This order will be presented along with the graphs to clarify which scenarios that are included. Figure 53 is an example that can be used to interpret these figures. A note is that the figures illustrates the number of different scenarios, not the total number of tests.

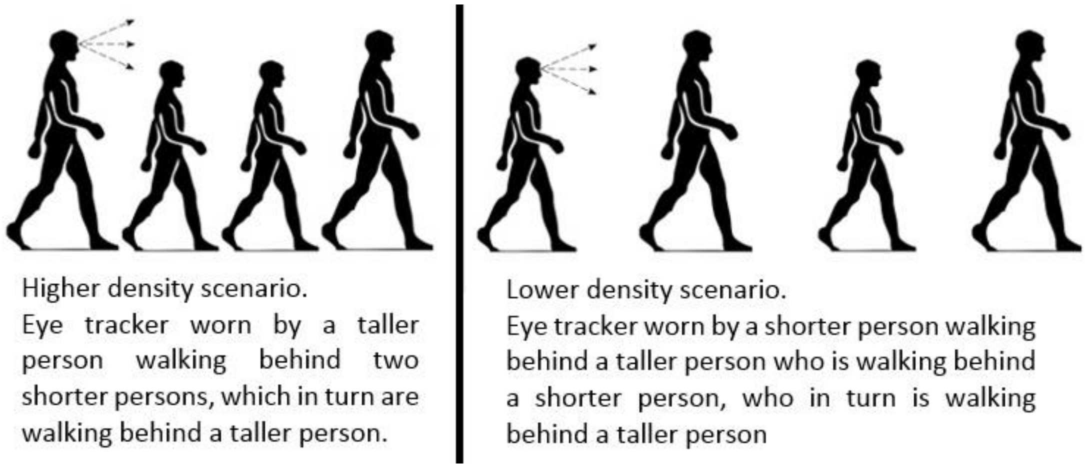

Figure 53 – Explanation of how to interpret the scenario figures

Furthermore, the graphs that will be presented shows the number of times the participants have focused their gaze on a specific area as a percentage of the total focus count.

5.2.2 Heights

The graphs in this section illustrates the gaze differences between people of different height and have been divided into two categories, shorter and taller people. The definition used is based on the person standing in front of the participant using the eye track glasses, i.e. if the person in front is taller, the participant will be placed in the "shorter" category.

By way of introduction, the scenarios included in these categories are presented. Figure 54 and Figure 55 illustrates the scenarios associated with shorter and taller people respectively. The graphs that follow are presented in the same order, i.e. the first graph will be for shorter people and the second graph for taller people.

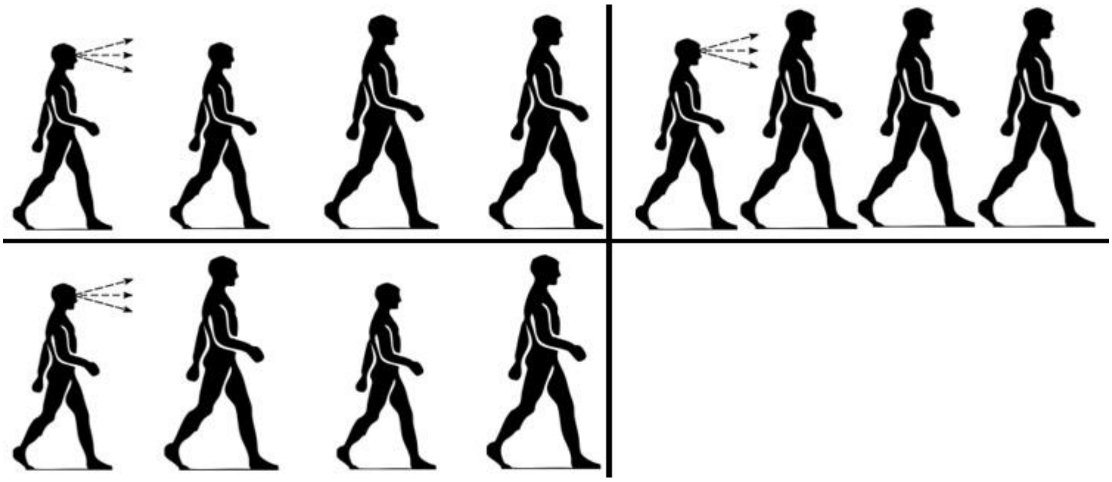

Figure 54 - Variations of scenarios for shorter people. Five tests were included

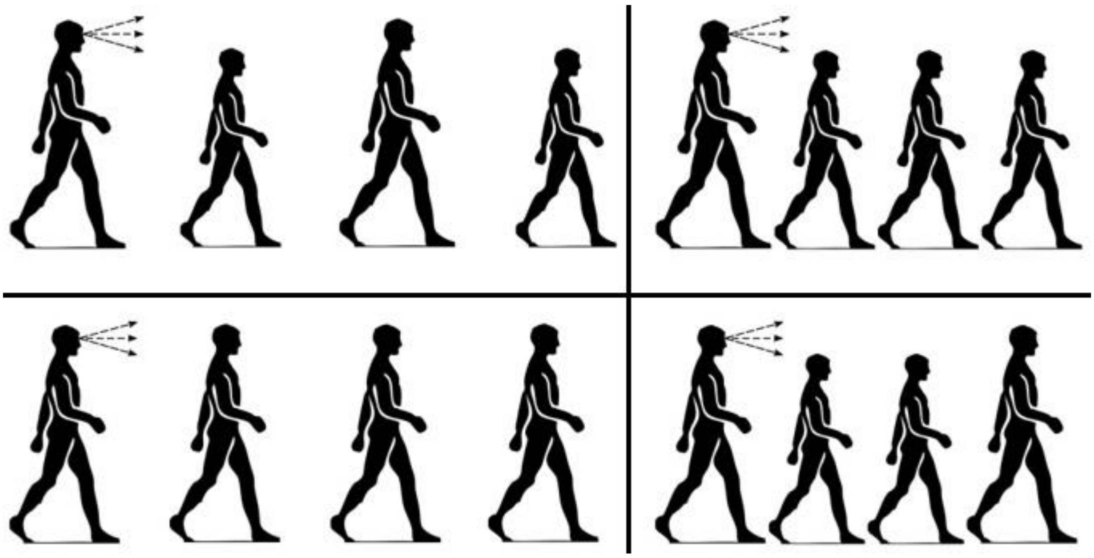

Figure 55 - Variations of scenarios for taller people. Seven tests were included

Figure 56 and Figure 57 show at which area shorter and taller people have looked. It is clear that both categories spend most of their time looking at the environment or planning their route.

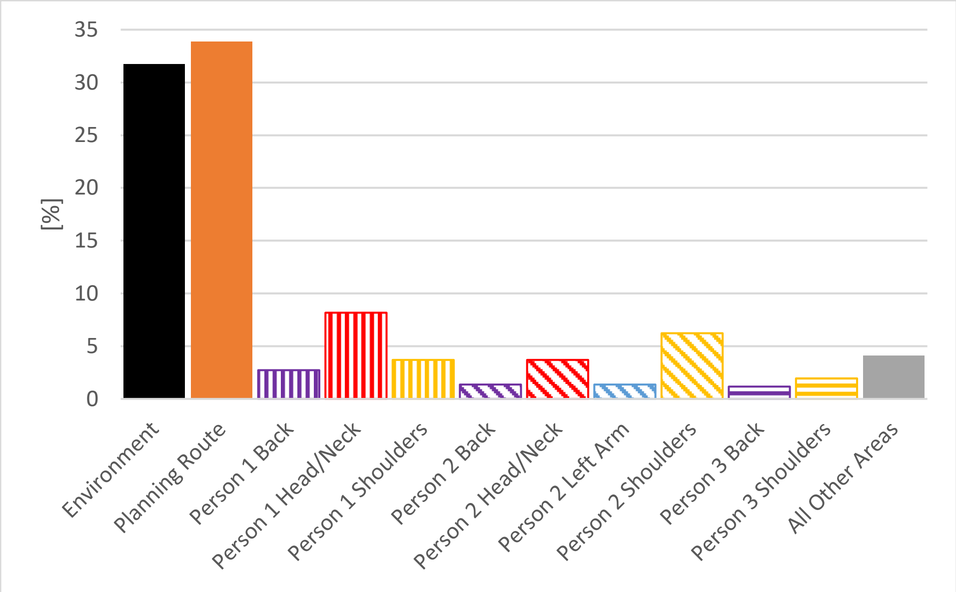

Figure 56 - Fixation areas for shorter people. 514 data points

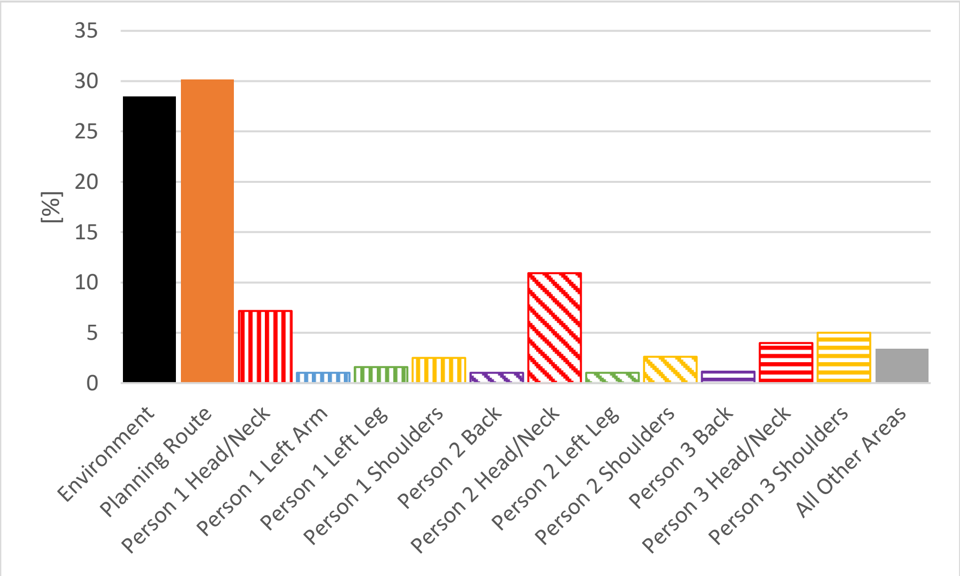

Figure 57 - Fixation areas for taller people. 879 data Points

Figure 59 and Figure 58 show which body part they are focusing on, regardless of which person they are looking at. These show a difference of about 15 percentage points between the “Head/Neck” values, suggesting that taller people tend to look at this area more often than shorter people. This being said, shorter people look more often at the shoulders and backs of the people in front.

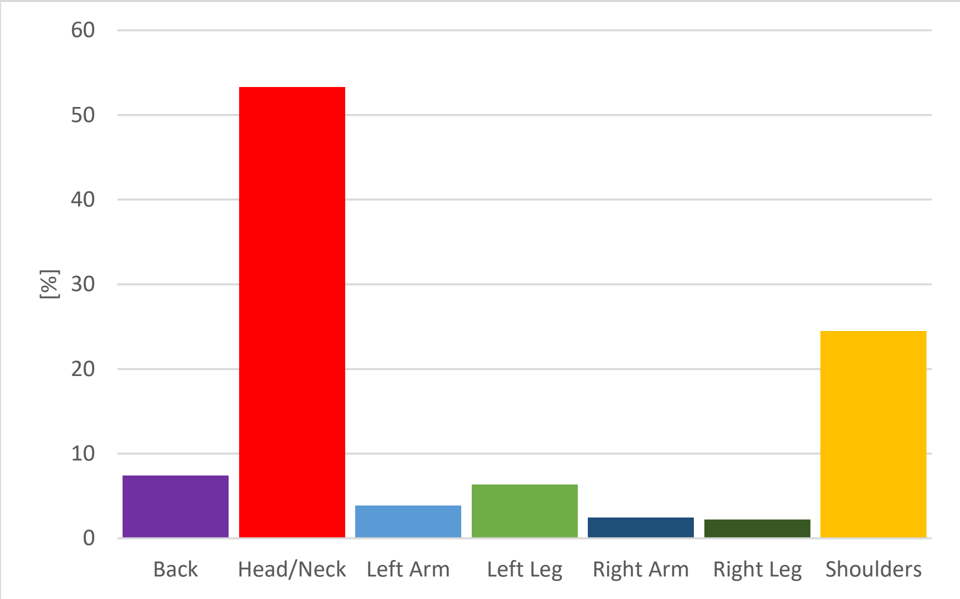

Figure 58 - Body fixation areas for taller people regardless of which person they are looking at. 364 data points

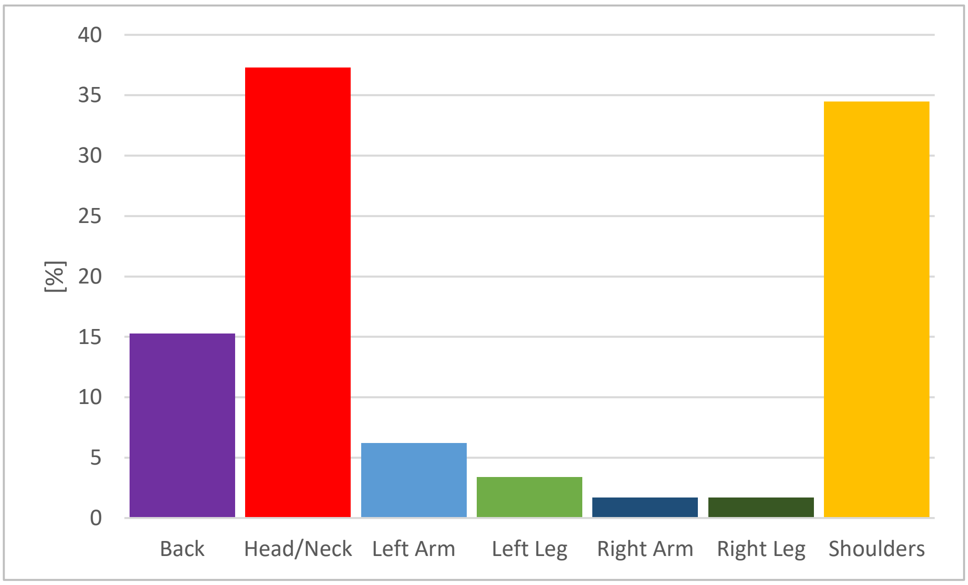

Figure 59 - Body fixation areas for shorter people regardless of which person they are looking at. 177 data points

Figure 60 and Figure 61 establishes which of the three people in front they are looking at. Shorter people are looking at "Person 1" more often than taller people by about 18 percentage points, which is expected since the taller people can see above the person in front of them. This is evident by the increase in "Person 2" and "Person 3" for the taller category.

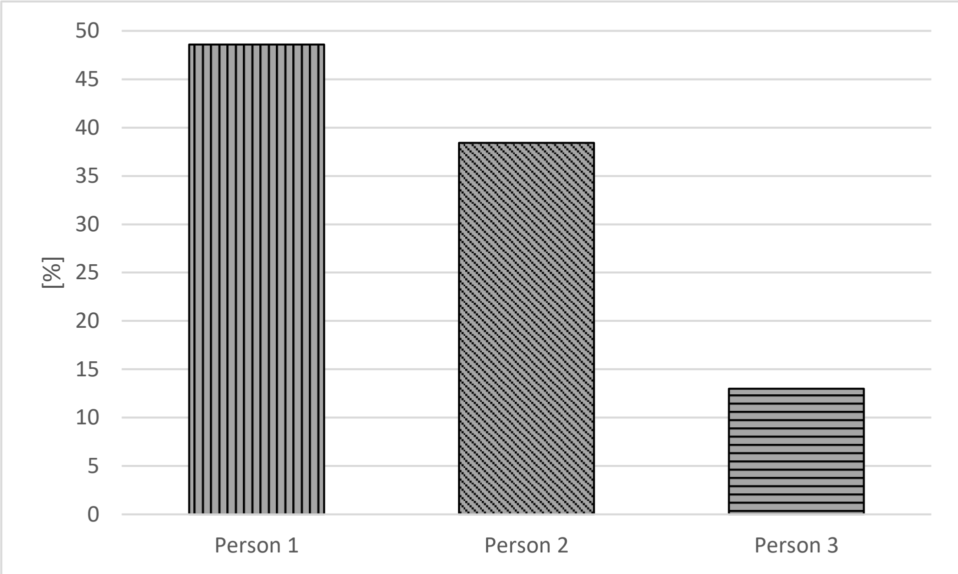

Figure 60 - Which person the shorter people are looking at. 177 data points

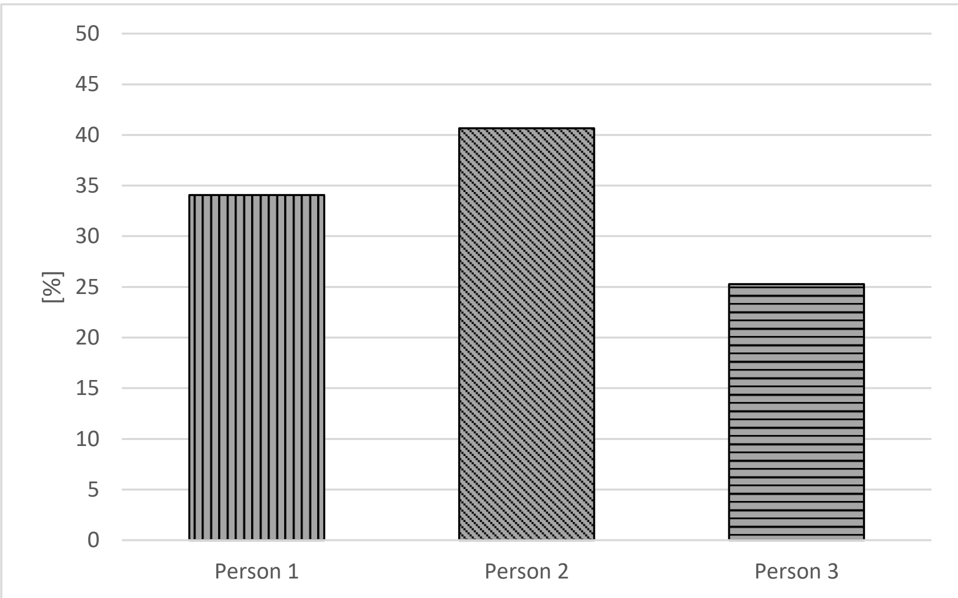

Figure 61 - Which person the taller people are looking at. 364 data points

5.2.3 Densities

The graphs in this section illustrates the gaze differences during different density cases. The density is divided into two categories, lower and higher densities. The definition of these are that everything larger or equal to 1.90 ped/m is considered a higher density and everything lower is considered a lower density. This puts roughly half of the different densities in each category.

By way of introduction, the scenarios included in these categories are presented. Figure 62 and Figure 63 shows the scenarios associated with lower and higher densities respectively. The graphs that follow are presented in the same order, i.e. the first graph will be for lower densities and the second for higher densities.

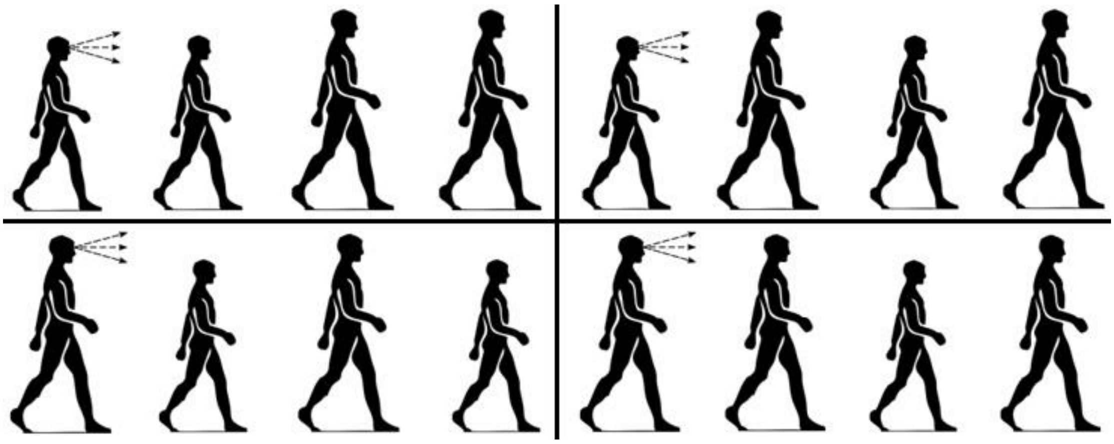

Figure 62 - Variations of scenarios for lower densities. Eight tests were included

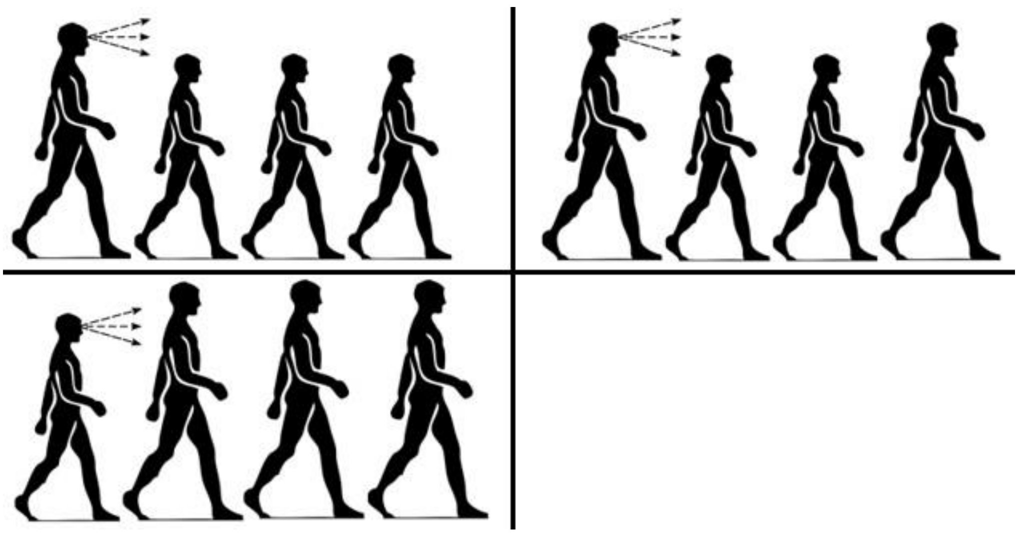

Figure 63 - Variations of scenarios for higher densities. Four tests were included

Figure 64 and Figure 65 show which areas were focused on during the different densities. It is clear that both categories spend most of their time looking at the environment or planning their route. However, during the lower densities the gap between environment and planning route, and the different body parts is much smaller than for the higher densities. Furthermore, people in the lower densities are looking at different body parts, whereas during the higher densities people tend to focus more at the head, neck and shoulders.

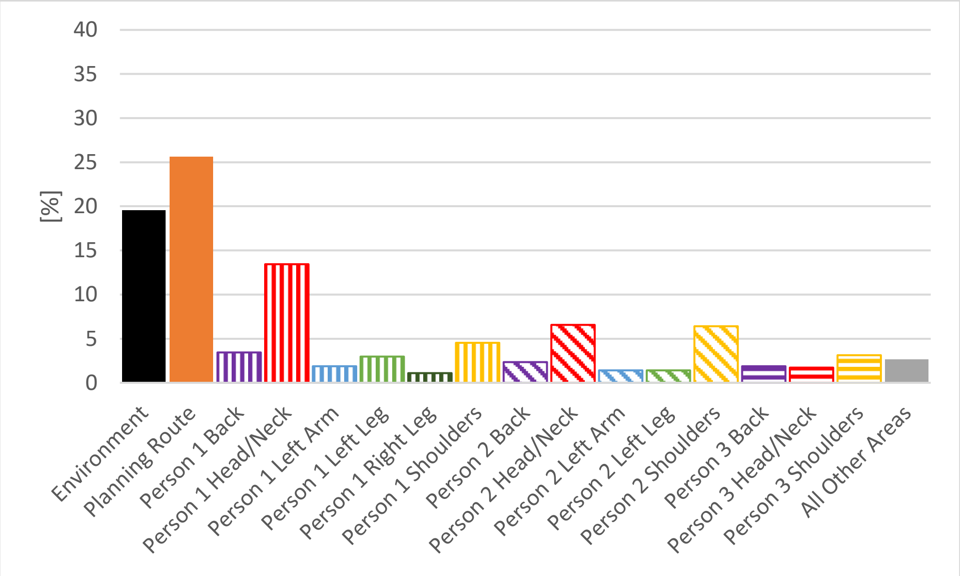

Figure 64 - Fixation areas for the lower densities. 640 data points

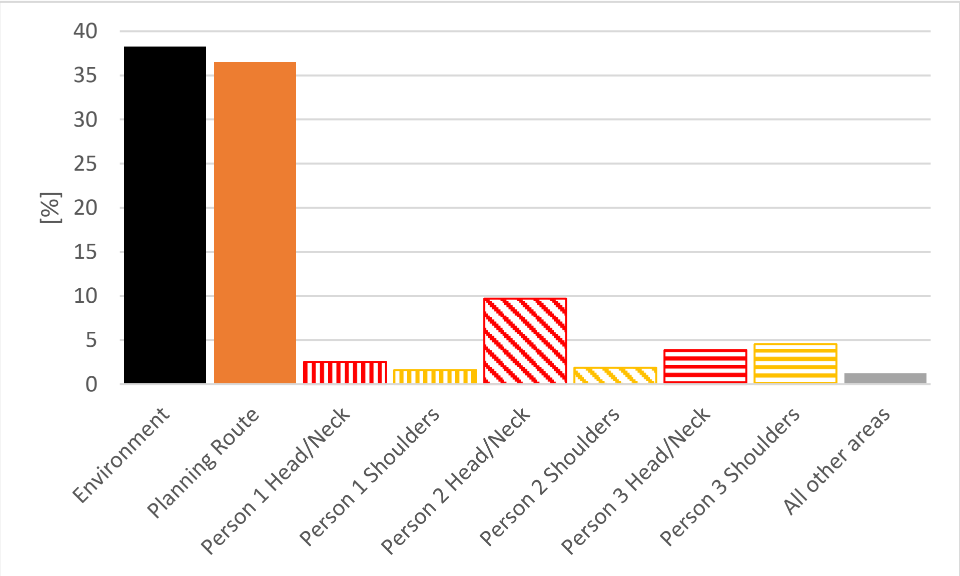

Figure 65 - Fixation areas for the higher densities. 753 data points

Figure 66 and Figure 67 show which body part they are focusing on, regardless of which person they are looking at. These show a difference of approximately 25% between the "Head/Neck" values, suggesting that during higher densities, people tend to look at this area more often than during lower densities.

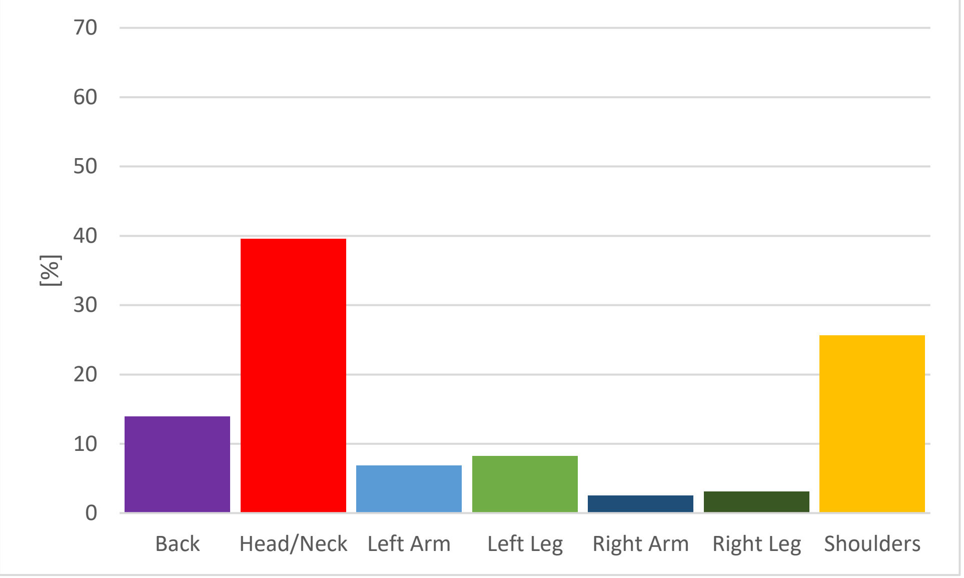

Figure 66 - Body fixation areas during lower densities regardless of which person they are looking at. 351 data points

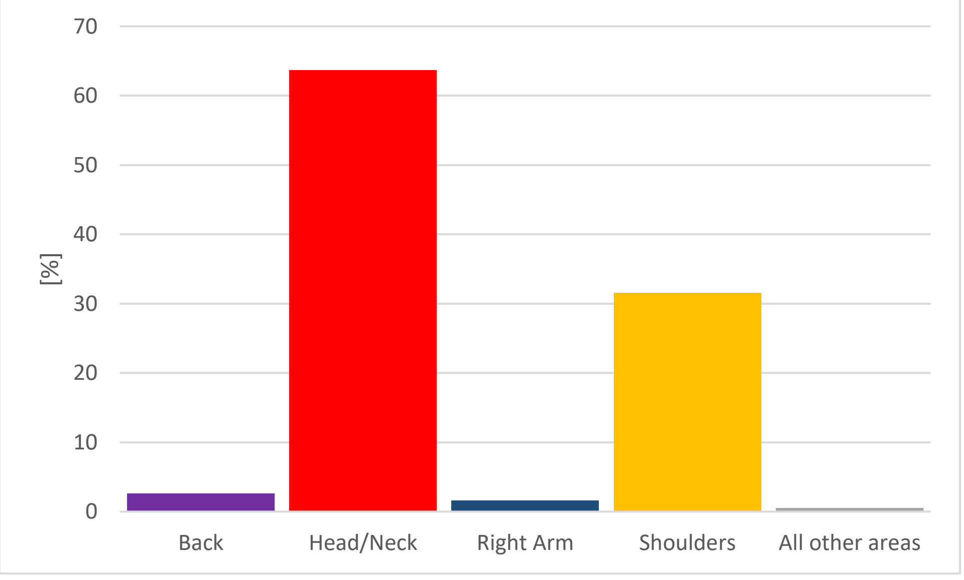

Figure 67 - Body fixation areas during higher densities regardless of which person they are looking at. 190 data points

Figure 68 and Figure 69 establishes which of the three people in front they are looking at. During the lower densities, people are looking at "Person 1" more often than during the higher densities by approximately 35%. This might be explained by body sway. Since there is more body sway at higher densities than at lower densities, this could mean that "Person 2" and "Person 3" become visible more often in these cases.

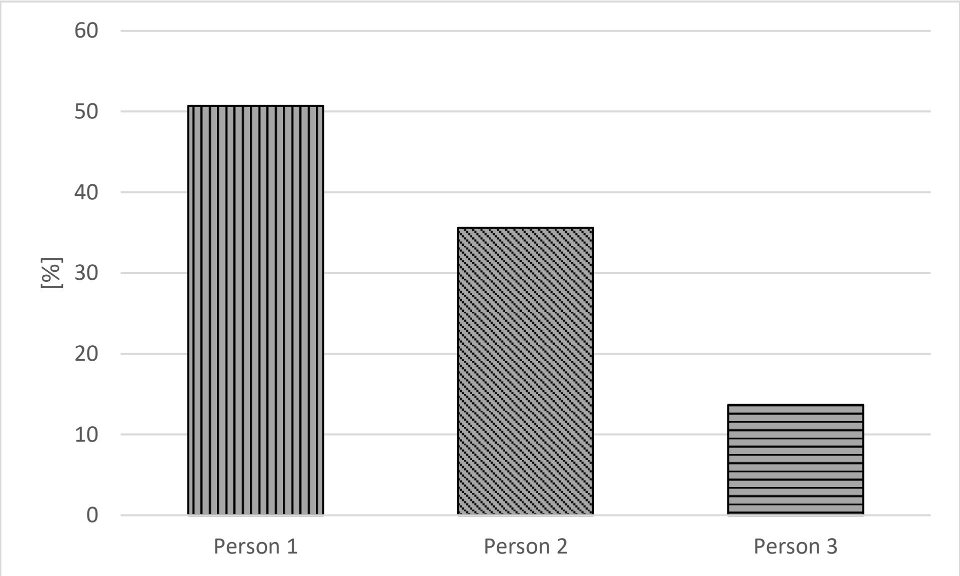

Figure 68 - Which person is looked at during the lower densities. 351 data points

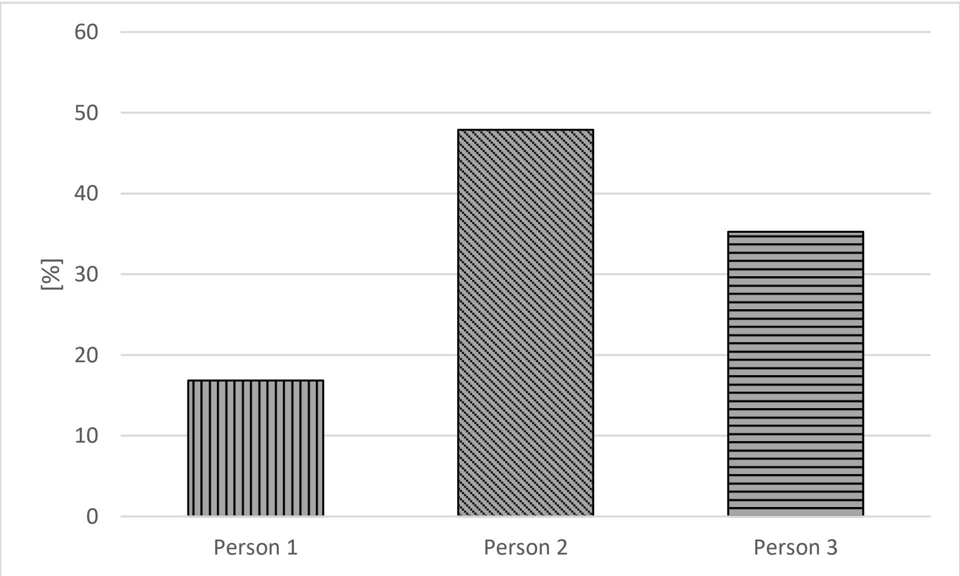

Figure 69 - Which person is looked at during the higher densities. 190 data points

5.2.4 Lower densities, shorter vs taller participants

The graphs in this section illustrates the gaze differences between people of different height during the lower density cases. They have been divided into two categories, lower density shorter and lower density taller people. The definition of the categories is a combination of the definitions in section 5.2.2 and 5.2.3.

By way of introduction, the scenarios included in these categories are presented. Figure 70 and Figure 71 illustrates the scenarios associated with lower density shorter and lower density taller people respectively. The graphs that follow are presented in the same order, i.e. the first graph will be for lower density shorter people and the second graph for lower density taller people.

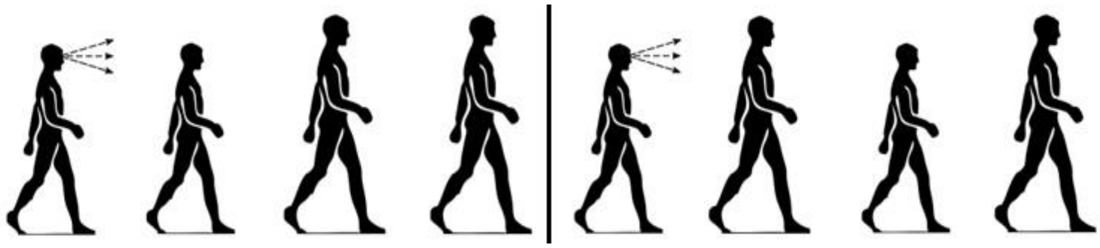

Figure 70 - Variations of scenarios for lower densities shorter people. Four tests were included

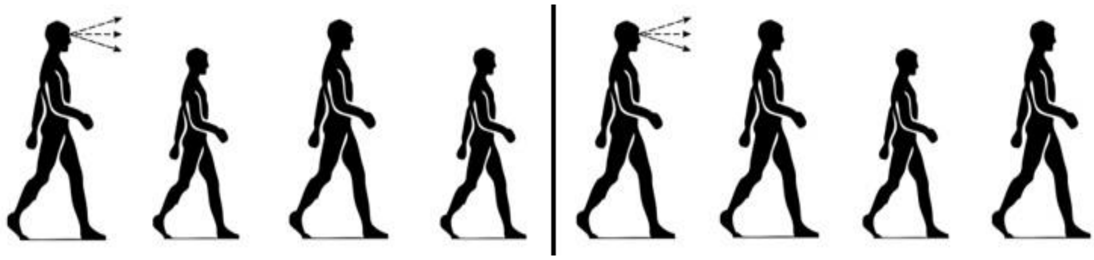

Figure 71 - Variations of scenarios for lower densities, taller people. Three tests were included

Figure 72 and Figure 73 show which areas were focused on by shorter and taller people during the lower density cases. Both categories spend most of their time planning their route, but for the shorter people the amount of time looking at the environment is only a few percentage points larger than that for the head and neck of person 1. This gap was significantly larger when comparing Figure 56 and Figure 57 in section 5.2.2. This is in line with what could be seen in Figure 64 and Figure 65 in section 5.2.3, namely that there is a density dependent difference.

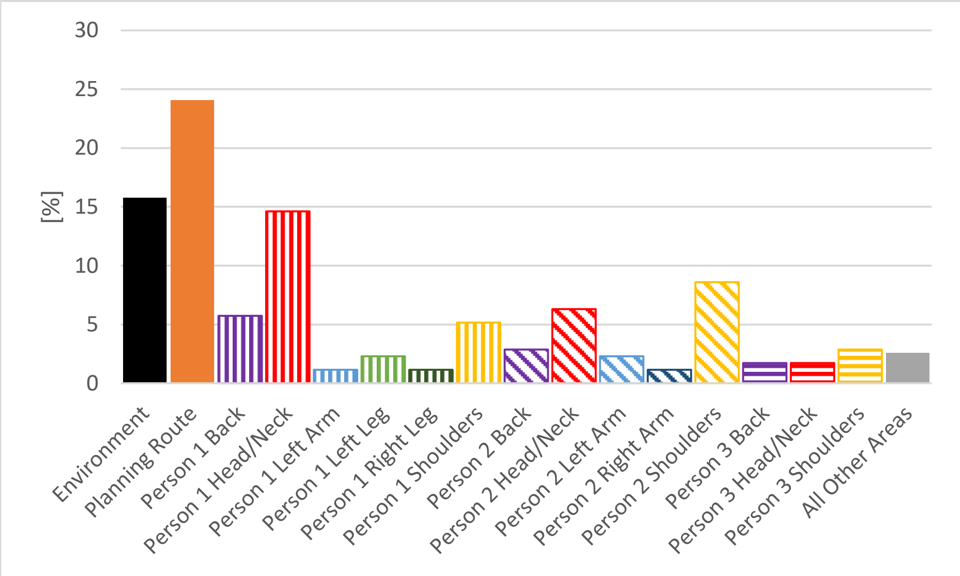

Figure 72 - Fixation areas for shorter people during lower densities. 349 data points

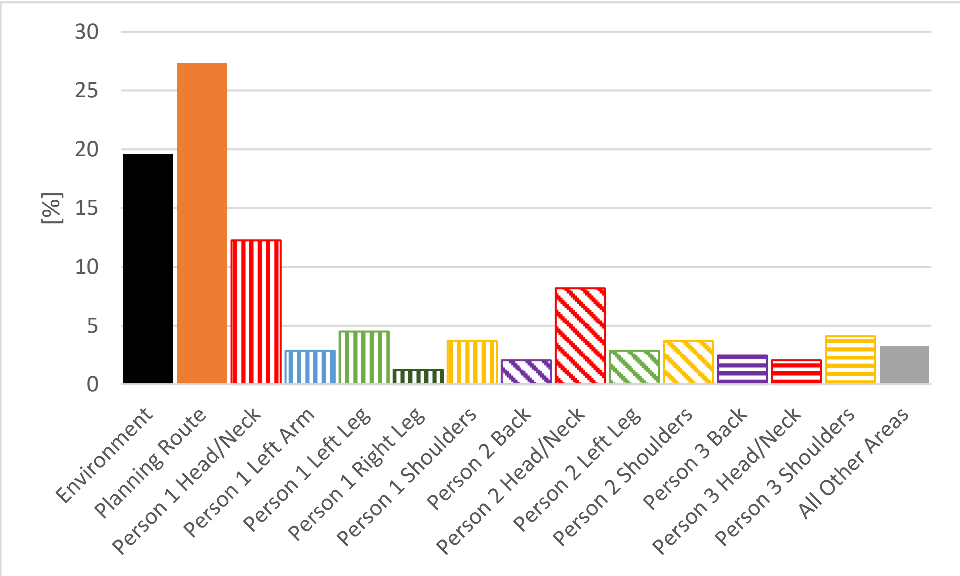

Figure 73 - Fixation areas for taller people during lower densities. 245 data points

Figure 74 and Figure 75 show which body part they are focusing on, regardless of which person they are looking at. The shorter people are looking more at the shoulder and back, while the taller people are looking more at the left leg, the head and neck.

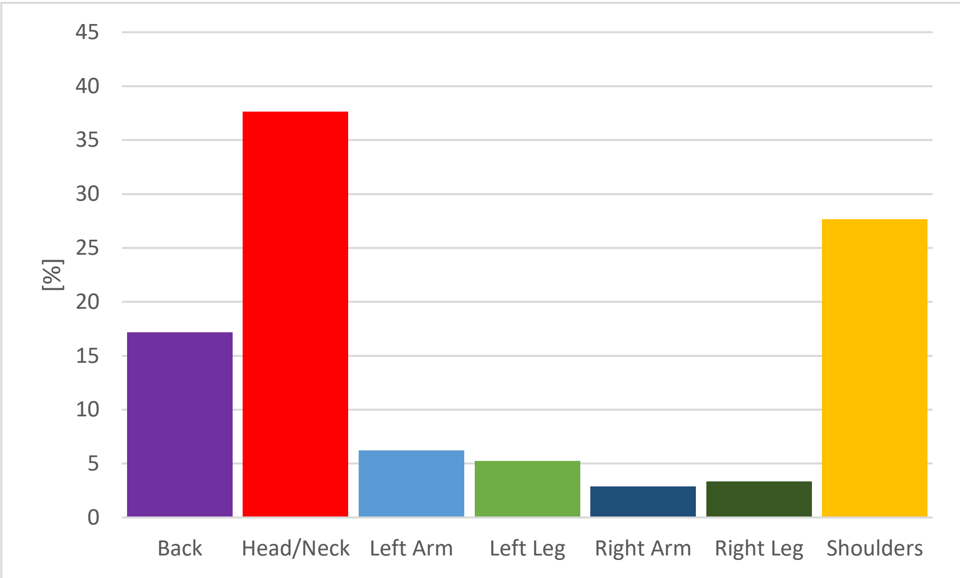

Figure 74 - Body fixation areas for shorter people during lower densities, regardless of which person they are looking at. 210 data points

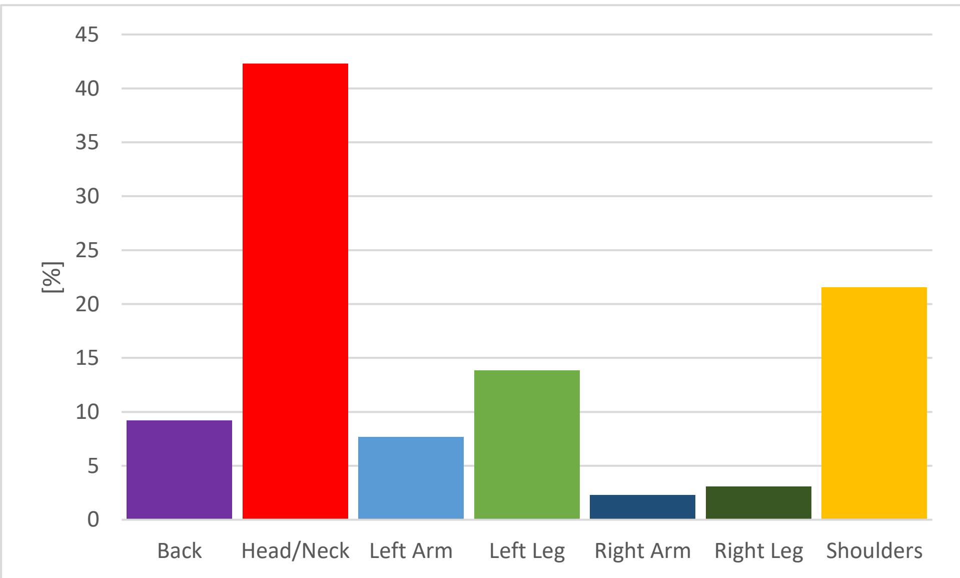

Figure 75 - Body fixation areas for taller people during lower densities, regardless of which person they are looking at. 130 data points

Figure 76 and Figure 77 establishes which of the three people in front they are looking at. There is no major difference and both categories focus most on “Person 1”.

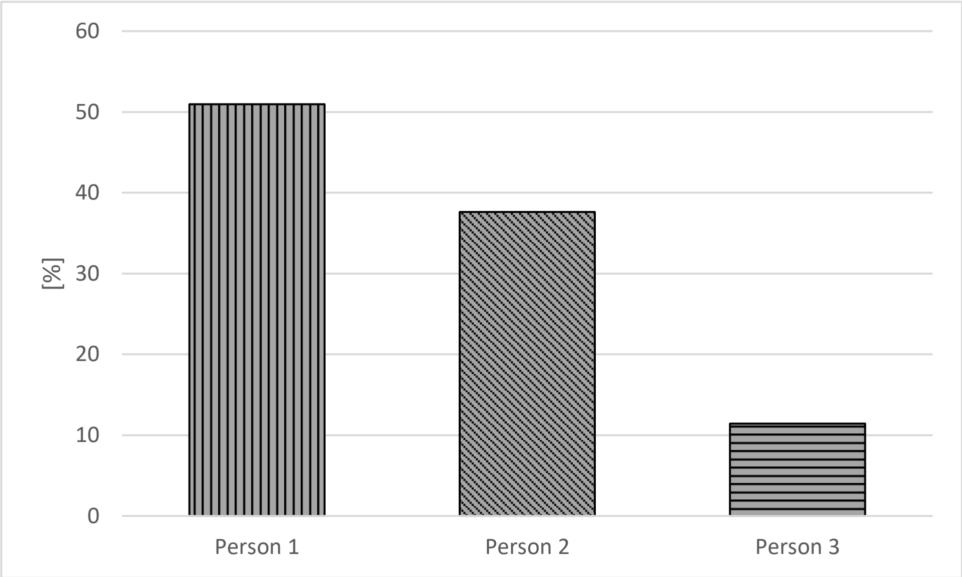

Figure 76 - Which person is looked at by shorter people during lower densities. 210 data points

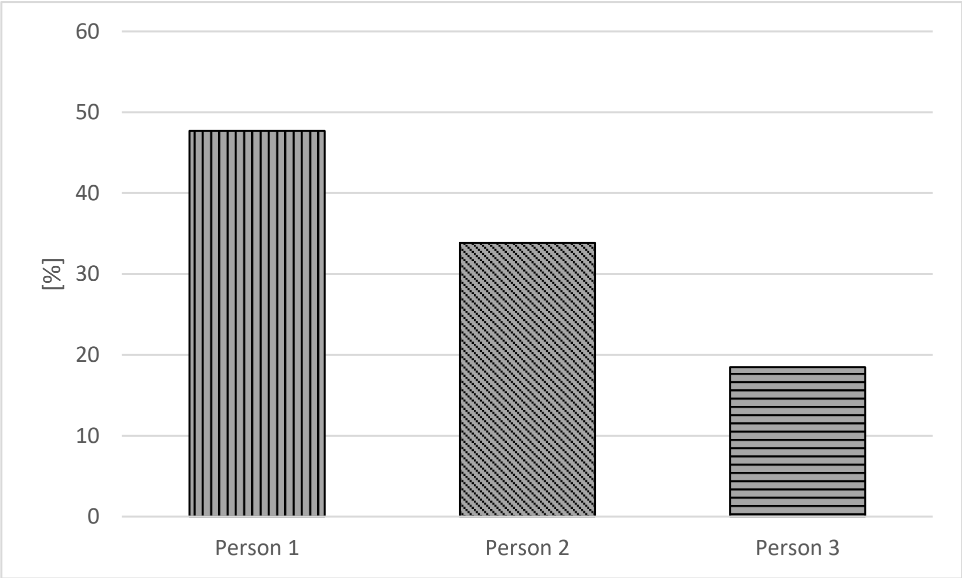

Figure 77 - Which person is looked at by taller people during lower densities. 130 data points

5.2.5 Higher densities, shorter vs taller participants

The graphs in this section illustrates the gaze differences between people of different height during the higher density cases. They have been divided into two categories, higher density shorter and higher density taller people. The definition of the categories is a combination of the definitions in section 5.2.2 and 5.2.3.

By way of introduction, the scenarios included in these categories are presented. Figure 78 and Figure 79 illustrates the scenarios associated with higher density shorter and higher density taller people respectively. The graphs that follow are presented in the same order, i.e. the first graph will be for higher density shorter people and the second graph for higher density taller people.

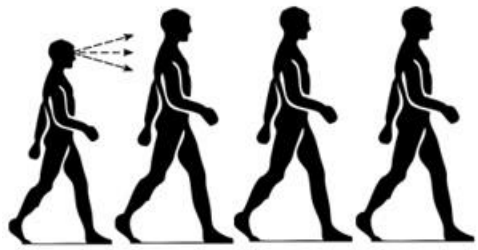

Figure 78 - Variations of scenarios for the shorter people. One test was included

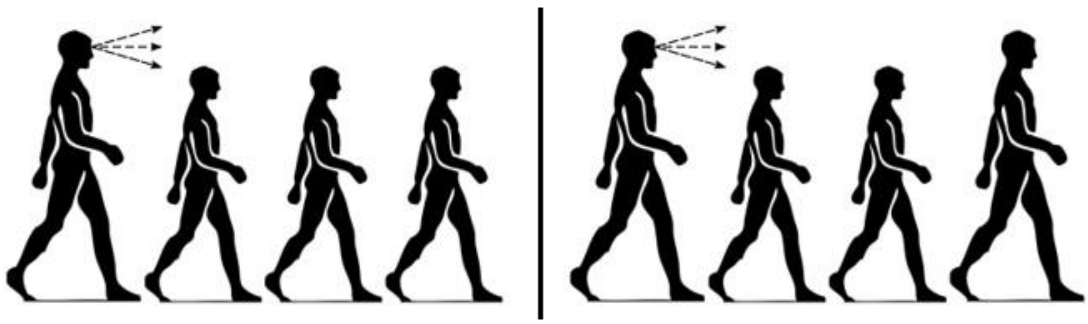

Figure 79 - Variations of scenarios for the taller people. Four tests were included

Figure 80 and Figure 81 show which areas were focused on by shorter and taller people during the higher densities. Both categories spent most of their time looking at the environment and planning their route, which also was the case for Figure 56 and Figure 57 in section 5.2.2. However, the taller people were looking at the head and neck of person 2 many times as well, which the shorter people never did.

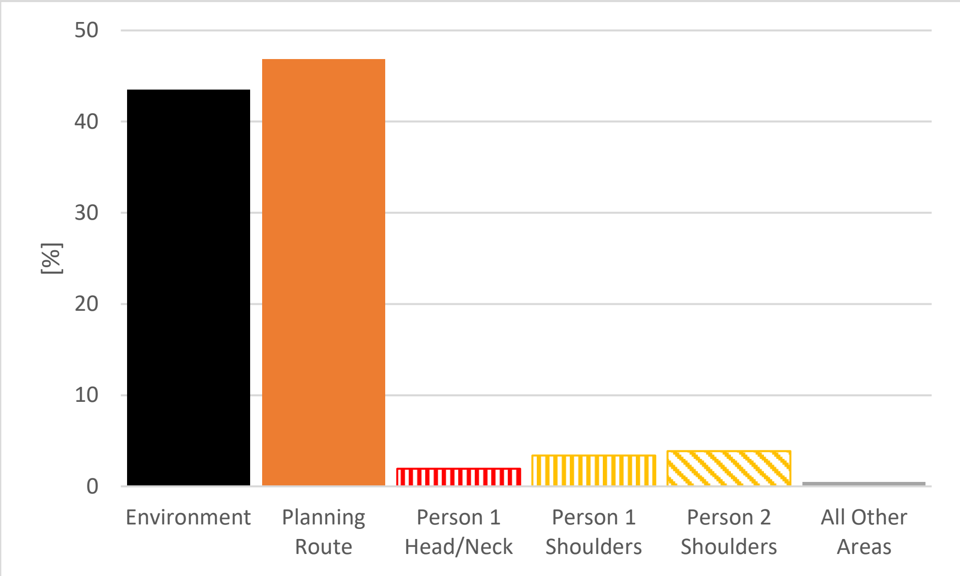

Figure 80 - Fixation areas for shorter people during higher densities. 207 data points

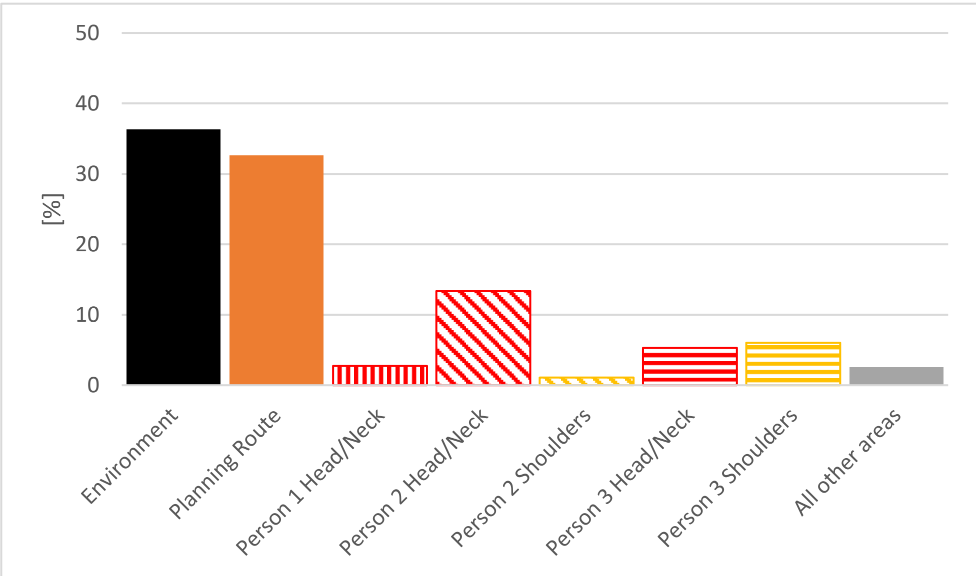

Figure 81 - Fixation areas for taller people during higher densities. 546 data points

Figure 82 and Figure 83 show which body part they are focusing on, regardless of which person they are looking at. These show a significant difference between the two categories, where the shorter people are focusing more on the shoulders than the head and neck, while the taller people do the exact opposite. This is different than in both section 5.2.2 and 5.2.3 where Figure 59 and Figure 58, and Figure 74 and Figure 75 respectively showed that both heights focused more on the head and neck. This was also the case for Figure 66 and Figure 67 in section 5.2.3.

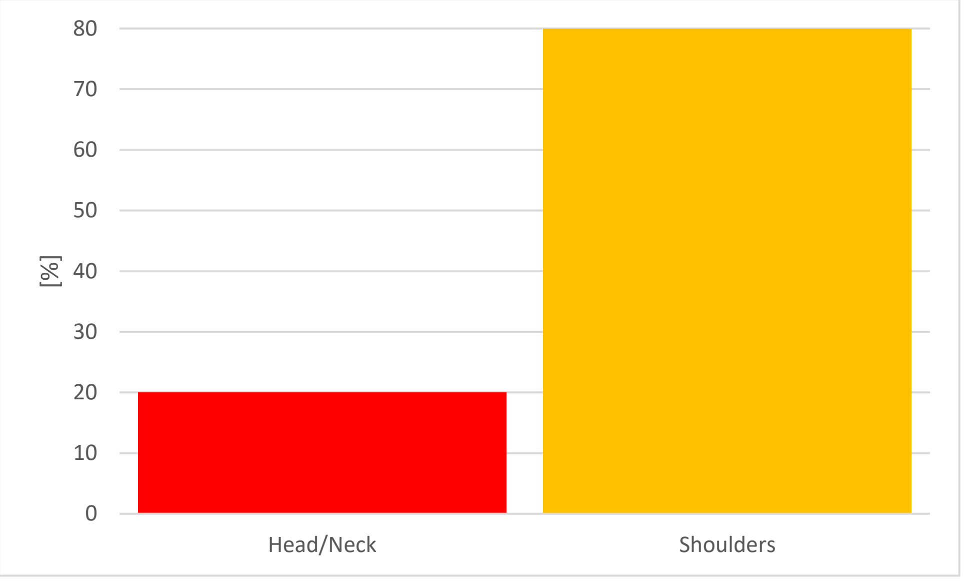

Figure 82 - Body fixation areas for shorter people during higher densities, regardless of which person they are looking at. 20 data points

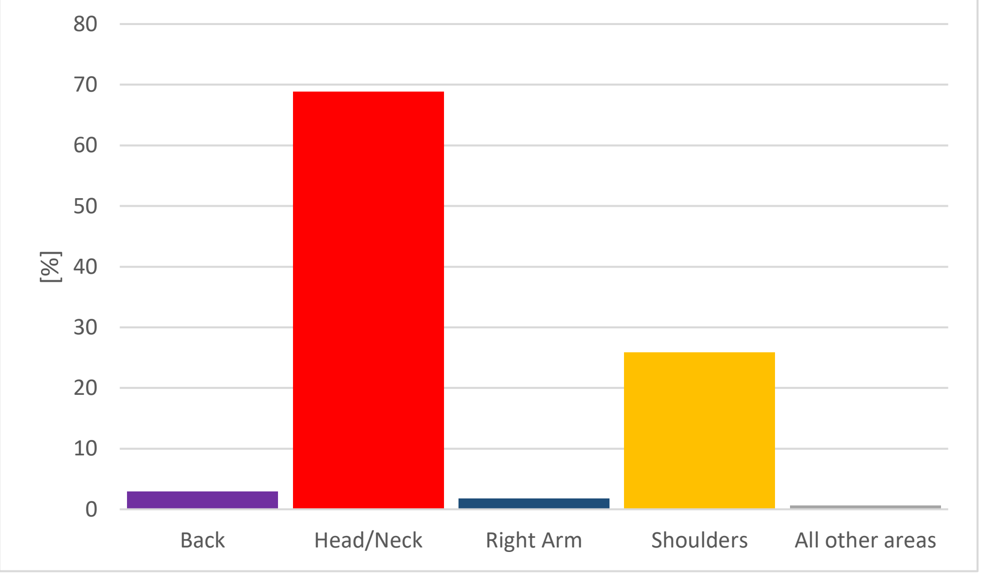

Figure 83 - Body fixation area for taller people during higher densities, regardless of which person they are looking at. 170 data points

Figure 84 and Figure 85 establishes which of the three people in front they are looking at. There is a major difference between the categories where the shorter people focused on “Person 1” at approximately 55% of the time, while the taller people only did it approximately 12% of the time. Furthermore, the number of times “Person 3 “was looked at was about 39% for taller people and about 5% for shorter people. That taller people looks less at “Person 1” was also shown in Figure 60 and Figure 61 in section 5.2.2, but Figure 76 and Figure 77 in section 5.2.4 did not show this when comparing the heights.

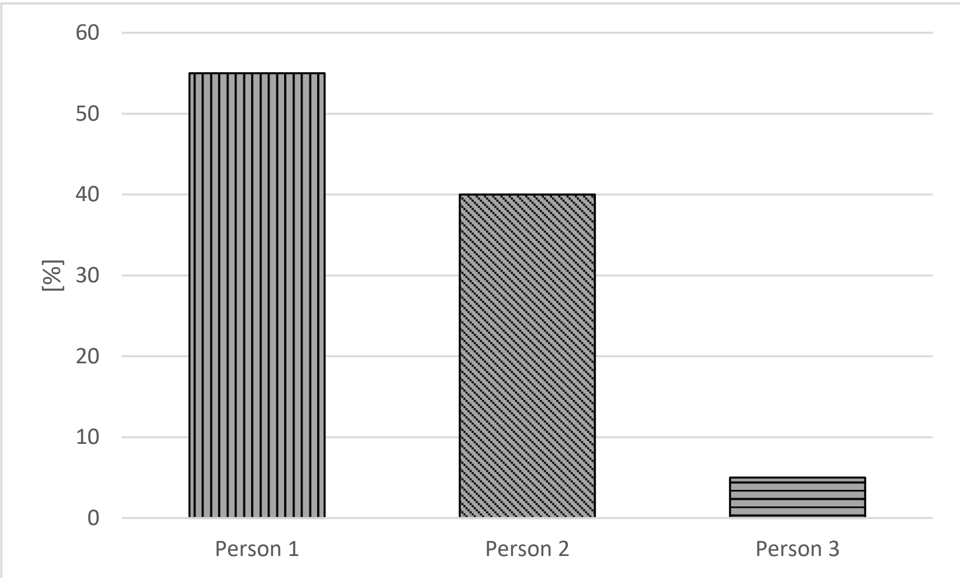

Figure 84 - Which person is looked at by shorter people during higher densities.20 data points

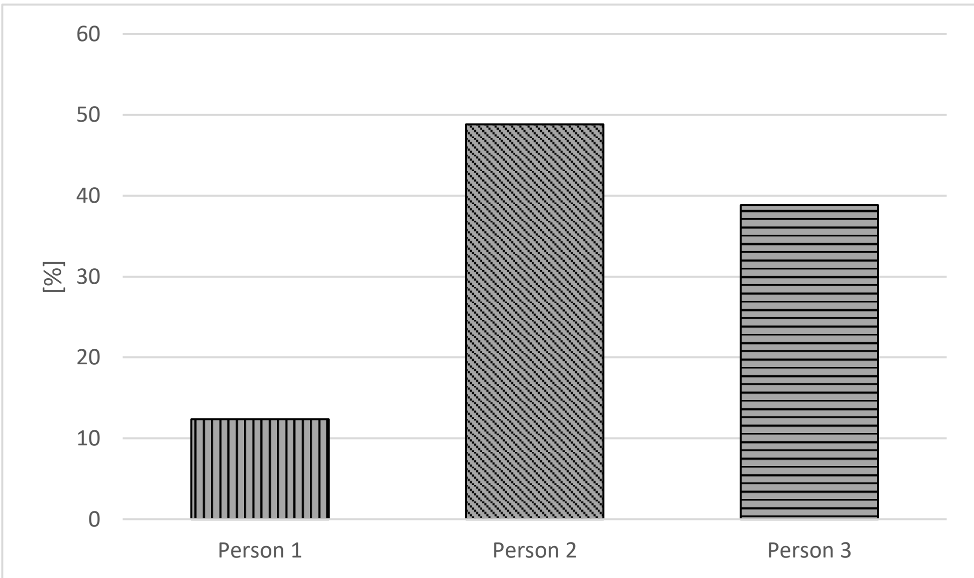

Figure 85 - Which person is looked at taller people during higher densities.170 data points

6 Discussion

This chapter discusses the results produced with the video and motion capture method, the methods themselves, and continued and future work regarding the data collected during the course of the thesis.

6.1 Results

In this section, the results from the video, motion capture and eye tracker analysis are discussed. The results from the video capture and motion capture experiment are presented as a combined result, dubbed “Optical capture”.

6.1.1 Optical capture methods

The main focus in this discussion will be on the two tests, D3 from the video capture experiment and B1.9 from the motion capture experiment, which the results are centred around. The results in the graphs cannot be compared directly because of the differences in preconditions, i.e. the experimental procedure and populations. For example, in the video analysis experiment, the speed during the tests depended on the occupant density, while in Dublin the speed was chosen from the start and only four people participated in each test. Furthermore, in the video analysis experiment the entire length of the circular path was used, which meant that the inter person distance during each test was determined not only by the participants’ preferences, but also the total space available. Whereas in the motion capture experiment, the participants could choose the distance more freely.

The average preferred walking speed of the participants differ with a value of 0.25 m/s between the two tests. In D3 and B1.9, the speeds were 1.23 m/s and 1.58 m/s respectively. Another factor that differs are the average heights of the analysed persons in the two tests, in D3 and B1.9 those heights are 1.82 m and 1.71 m respectively. In section 2.2 it was said that taller people generally walk faster, however the comparison shows the opposite. This might be explained by the fact that the instructions given to the participants were different between the two experiments. In Lund participants were told to walk at the speed they used to get to the venue, whereas in Dublin they were asked to walk as if they were going to lunch.

As it was mainly students that were recruited for the video capture experiment, many of the participants knew each other. It was noticed that they were talking to each other during the experiment, even turning around to talk to the person behind them in some cases. When walking in a crowd, a person is not always by him or herself, they might be there with one or more friends and will most likely engage in conversation. However, it is not likely that this movement will be done in a single file fashion rather than the people moving as a group, something more similar to the double file arrangements. When they were instructed to walk in single file, the fact that they were friends may have had an impact. Looking at the videos it is clear that they aren’t walking directly behind each other, some of them are walking a bit offset from the person in front. Some were even walking offset by a full body width, even after being told numerous times. However, if the width of the path had been a bit narrower it might not have occurred. An additional factor that might have affected the results is the choice of tests and persons to analyse. In the video capture analysis, a test where the crowd movement could be seen as laminar and a test with crowd movement that showed tendencies of stop-and-go waves were chosen for the analysis. Then, two participants were chosen, at random, to be analysed. If two other participants would have been chosen, the results might have been different. For the motion capture analysis, a test with an average speed similar to D3 was chosen, as well as a test with a speed of 1.3 m/s which was defined as the normal speed during this experiment. The analysed participants were also randomly chosen by the authors.

However, there are some similarities in the results from the experiments. The average inter person distance was the same, 0.83 m at speeds around 0.5 m/s, which is very interesting because that gives an opportunity to compare their step length and contact distance. As previously mentioned, the average height between the two tests differed by 0.11 m in favour of the video analysis experiment. This is similar to the difference regarding the average step length, which was 0.09 m in favour of the same experiment. If the inter person distance is the same but the step length is longer, the contact distance should naturally be shorter, which is the case here. The contact distance is 0.10 m shorter in B1.9, which was presented in Table 7. Having the same inter person distance in the two tests at similar speeds indicates that it might not be necessary to have as many participants as were recruited for the experiment in Lund to get relevant single file crowd movement data. However, since the participants in Dublin chose their inter person distance solely on their personal preference regarding a comfortable distance, cultural differences might have had an impact on the inter person distance. In Lund, the inter person distance was governed mainly by the available space within the enclosed path.

Regarding contact distance, measurements were taken for the posterior and anterior during the analysis of the video capture experiment. However, these are not included in the graphs. This was done in order to present graphs using the same type of measuring points from both the video capture experiment, as well as the motion capture experiment. The determining factors for the contact distance was instead the rearmost heel and the foremost toe which, as described in section 5.1.5, is not always the case. In test A3 from the video capture experiment, where the occupant density is higher, it is more likely that the posterior and anterior are the determining factors for the contact distance. During both test D3 from the video experiment, and test B1.9 from the motion capture experiment, the feet are the dominant factor that determines the contact distance. The indication that step length affects the contact distance, points to the height as being a determining factor as well.

In both Figure 46 and Figure 49, there are high peaks in the beginning of the graphs which affects value of the average contact distance. It seems like the person behind, “Person B”, takes a larger step to catch up with the person in front, “Person A”, and then continues to walk “normally”. In B1.9 on the other hand, something seems to have happened to the marker at the start of the measurements. However, it does not seem to have any large impact on the average contact distance. The peaks’ appearances are not the same in the two methods. It is much smoother in the motion capture experiment, which most likely is an effect of the higher sampling frequency for that experiment. The peaks should be become “higher” and not as “rugged” in the video experiment if the sampling frequency was increased.

In some of the graphs e.g. Figure 36 from the motion capture experiment, it is possible to see differences, in the form of small troughs, on the left feet of both persons compared to how the same feet are plotted in Figure 35 from the video capture experiment. The small differences most likely occurred when the markers on the left foot became obstructed by the right foot. When this happens, Codamotion tries to interpolate between the position where the marker was last seen and the position it has when it reappears. It seems to have had some trouble doing this. Obstructed feet were an issue in the video analysis as well where an estimation of the foot's position was made.

In section 5.1.2, where the absolute inter person distance is shown, there are some trends pointing at stop-and-go waves. These waves affect the inter person distance, contact distance and step length. The wave's travel can be seen, as it appears on "Person B" a short time after "Person A". While looking at the video of the D3 test from the video capture experiment after the analysis was completed, it became apparent that there were clearer stop-and-go waves at other times during the test.

There are connections between walking speed and inter person distance, but also between walking speed and step length, which is claimed by Jelić et al (2012). Figure 50 shows that this is the case, but it seems that inter person distance and step length have the same linear relationship in this chart. Probably, if adding more data points the trend line might look more like a logarithmic one because it is not likely that the step length or inter person distance is that high when the velocity is zero. A logarithmic trend line with these four data points each gives a coefficient of determination of 0,97 for the step length and 0,98 for the inter person distance which might strengthen that argumentation. However, this way of showing the relationship between the parameters has never been done before with that many participants walking at the same time and it is therefore an important outcome of this project. The contact distance on the other hand seems to show a linear relationship to the velocity which gives approximately a contact buffer of 0.28 s. With an extensive analysis, it might be possible to quantify this relationship and possibly conclude that measuring the inter person distance is sufficient to determine the step length and that the contact distance follows a linear relationship which has a constant contact buffer. This is something that's worth investigating in the future.

It is important to consider that the experiments conducted during the course of this thesis are not an accurate depiction of reality. Each test was performed in either a single file or a double file arrangement where the participants were told not to overtake one another, while in reality people are moving in all directions and overtaking is done regularly. However, since both methods requires markers to be visible it is difficult, and even impossible in some cases, to accurately depict this kind of movement in these types of experiments. Furthermore, the need to install equipment on the participants means that the methods produce experimental data rather than naturalistic data. The equipment can influence the behaviour of the participants which decreases the accuracy of the depiction even more. A more naturalistic approach would be to set up cameras at a venue and observe the people, but this means that the measurements would be less accurate and more user dependent since there would not be any markers to track.

6.1.2 Eye tracker

Looking at the results from the eye tracker it is evident the participants are planning their route or looking at the environment most of the time, but when they are looking at a person, the areas that they focus on the most are the head, neck and shoulders. There are differences between the categories though.

Figure 59 and Figure 58 show that the amount of times that participants of different height has looked at the head and neck area differ, and that taller people do it more often. This is expected since the definition for being considered as "taller" is that the person ahead is shorter, meaning that the taller person can see above the shorter person. This means that the taller person can see the head and neck of the person ahead of the shorter person more easily than a shorter person walking behind a taller person. This is evident when looking at Figure 60 and Figure 61, where the shorter people are focusing mostly on "Person 1" while the taller people are focusing on "Person 2". The increase in number of times a participant has looked at the back of the people in front for the shorter people category strengthens this reasoning.

When comparing Figure 66 and Figure 67, there is a clear difference between the lower and higher densities. Although both categories have the head, neck and shoulder regions as their favoured focus point, the participants in the higher densities spend a collective 95% of the time looking at these areas while the same number for the lower densities is 65%. This is not unexpected since during the higher density cases, the number of pedestrians/m^2 can be as high as 2.87. This means that the participants are standing so close to each other that they cannot see the other areas, or at least have difficulties doing so. Figure 68 and Figure 69 show that during the lower densities the main focus point is "Person 1", while it's "Person 2" for the higher densities. Furthermore, the amount of times the participants have looked at "Person 3" is higher during the higher densities. For the taller people this is expected from what has been discussed previously, but it goes against what was seen for the shorter people. This might be explained by body sway, explained in section 3.4, which enables the participants to see past the person in front of them, if their body sways aren't synchronized. Looking at the video, this pattern is noticeable.

The lower density, shorter and taller people cases show some similarities to what has been discussed so far. Figure 74 and Figure 75 show the same pattern as Figure 59 and Figure 58 in that the taller people are looking at the head and neck more often than the shorter people are, although the difference is not as profound during the lower densities. The difference noticed in Figure 66 and Figure 67, that during lower densities people tend to look at more areas of the body, is visible here as well. Comparing Figure 76 and Figure 77, it is clear that the difference between the graphs are minor. Both the taller and shorter people are mainly focusing on "Person 1", followed by "Person 2". This is in line with what was shown for the lower densities in Figure 68 and Figure 69, however it goes against the comparison of the heights in Figure 60 and Figure 61. This could implicate that which person you are looking at depends more on the density case rather than the length.

In the higher density, shorter and taller people cases there are some differences from what has been discussed so far. Looking Figure 82 and Figure 83, it can be seen that the shorter people spend most of their time looking at the shoulders of the people in front, followed by the heads and necks. This is the only case where the participants are focusing more on the shoulders than the head and neck. Figure 84 and Figure 85 then show that the taller people look mostly at “Person 2”, which is in line with what was shown for the heights in Figure 61 and the densities in Figure 69. The shorter people, however, only show similarities regarding “Heights” from Figure 60 and not “Densities” from Figure 69. This would implicate that the length has more impact on which person you are looking at rather than the density case, which is the opposite of what was discussed for the lower density, shorter and taller people cases.

A factor that must be taken into consideration, especially for the higher density, shorter and taller people cases, is the varying number of tests and data points for the different categories. Table 2 shows that ¼ of the single file tests didn’t get registered due to technical issues with the eye tracker, leaving 12 tests for the analysis. More tests were completed for the lower densities than the higher densities since the participants were only available for a limited time, and the higher density tests took longer to complete. The difference would have been there even without the loss of tests. Regarding the difference in tests included in the “Heights” category, there are more tests for the taller people simply because of the loss of tests. The variation of the number of data points is hard to get rid of, since it depends on whether or not the participants are focusing their gaze and if they are changing their focus. Looking at Figure 80 and Figure 81, which had one and four tests included respectively, the number of data points are 207 and 546 respectively. Had the taller people changed their focus as often as the shorter person, they would have generated almost 300 more data points than they did. Looking at the “Heights” category, it is no surprise that the taller people generated more data points considering that more tests were carried out with taller people. The difference in data point from the “Densities” category might seem unpredicted, but the explanation is simple. It takes longer for the participants in the higher density cases to pass the area where the analysis is performed, meaning that they have more time to generate data points by shifting their focus. Returning to why this is especially important for the higher density, shorter and taller people cases. When comparing Figure 82 and Figure 83 or Figure 84 and Figure 85, it can be seen that the shorter people have only generated 20 data points by focusing their gaze on the people in front, while the taller people have done it 170 times. Furthermore, considering that the shorter people category only had one test included in the higher densities, this result can hardly be used as an illustration of reality. There is always an individual variation between the participants within the categories, but in this specific category this variation cannot be observed.

Relating to the data points is the fixation assumption made in section 4.2.5, in which all fixations larger than 60 milliseconds are counted evidence that the participant has looked at and registered the area, since this is a direct cause of the number of data points. Considering that the time to focus on and register objects varies depending on the object, this assumption is extremely conservative. However, even if the participant hasn’t registered the observed area consciously, they might have done so subconsciously. Considering this, the assumption is regarded as justified with the notion that it is conservative.

It has been observed that in all categories, “Environment” and “Planning Route” are the areas that the participants focus their gaze on most of the time. This might have been different if the set-up had been different. In Figure 10 the experimental set-up was shown. As can be seen, the venue is big and open in all directions and offer a lot of potentially “interesting” things to look at. If the venue had been empty or had sections that were walled off, the time spent looking at the environment might have decreased. Furthermore, it became clear that there were groups of participants that knew each other, which in itself is not a surprise considering the recruitment process described in section 4.1.1, but this meant that these groups were talking amongst themselves during the tests even though they rarely stood next to each other. As was stated in section 0, if the participant wearing the eye tracker looked behind themselves it counted as looking at the environment. This behaviour was observed in a few of the cases, in some more than others. “Planning Route” could possibly have been removed entirely if the path was walled off entirely, in the same way one of the straight sections is, as seen in Figure 10, or if experiments were performed in a straight corridor. The set-up is also considered as the reason for “Left Arm” and “Left Leg” being observed more often than “Right Arm” and “Right Leg”. Since the path can be considered as a large left turn, it seems natural that the participants will focus more on the left sides of the people in front rather than the right side. If they would have been walking in the other direction, they most likely would have focused more on the right side.

When the participants arrived and were introduced the experiment, they were told that the eye tracking glasses were an ordinary pair of glasses with a video camera attached to them, which would be used to get their perspective during the tests. One participant asked if they were eye tracking glasses. He had taken part in another experiment which had used eye tracking at was familiar with the equipment. The other participants proceeded to ask him questions about the equipment, which lead to all the participants obtaining knowledge about the eye tracking glasses. During the early tests, comments aimed towards the participant wearing the glasses from the other participants were in the line of *“Be careful where you look, they can see it”*. This might have affected the results, the wearer could possibly force him or herself not to look at, or indeed look at certain areas. The effect of this is regarded to be isolated to the beginning of the tests when the participant has just put on the glasses. Consider a person that is told to breathe manually, after a while the person starts breathing subconsciously again. The same effect can be considered for this.

To summarise, the majority of the time people spend looking at the environment or planning their route. Despite this, there seems to be some sort of correlation between where people look when moving through a crowd and their heights as well as the density case present. However, due to the limited tests and data points the following list should only be considered as an indication, which is why no inferential statistical testing was performed during this thesis. More research is needed to find the exact relationships.

6.2 Methods

Both the optical motion capture method and the video analysis method have been used to track inter person distance, contact distance and the positions of the feet. In this section, the advantages and disadvantages of the methods will be discussed. Furthermore, a review of the list presented in section 1.1 will be performed to check which parameters could possibly be investigated using these methods.

One of the advantages of the video analysis method is that it is easy to prepare for since the equipment you need is, at its core, are video cameras and a video analysis program. The other method requires and optical motion capture system which isn’t cheap, the cost of the system used in this thesis was around €27000 per sensor and around €10000 for the software when it was acquired in 2006. Note that even though current prices have come down since then due to technological advancement it is still an expensive system, one of the markers currently costs around €80 and the battery pack around €300. However, the video analysis method could turn out to be expensive as well, depending on which cameras and software is acquired.

The accuracy of the results depends on different aspects of the two methods. One thing that the methods have in common is the marker placement. To accurately track the joint's position the marker must be placed on exactly the right spot, which can be a challenge without a broader physiological knowledge. This being said, the accuracy of tracking the markers in real time is different between the methods. For the Codamotion system, the software Codamotion ODIN tracks the markers' positions in the measured volume and compiles them into a spreadsheet, automatizing the analysis process. In Kinovea the user must manually click on the markers every time step to get their positions, and then register them into a spreadsheet. A user uncertainty tests was performed in order to see how much the values changed depending on which of the authors took the measurements. The test was performed during the same time steps and the values differed by 3-4%. A note is that Kinovea has a function where it is supposed to track a marker automatically, but this was very unstable and did not work for more than a few time steps. It is then not surprising that the video analysis took considerably longer time to perform. Of the analyses performed in this thesis the video analysis took 50 man-hours while the optical motion capture analysis took four hours (the duration of the experiment). What is important to note is that during those timeframes, the video analysis was performed on two tests with two participants in each test, while the optical motion capture analysis was done on all participants during all tests. This means that on average 12.5 hours were spent on each participant in the video analysis, but only 0.25 in the optical motion analysis. This difference would be larger if the resolution, or the size of the time steps, was the same for each method. The video analysis was performed with a time step of 0.12 s, while the motion capture analysis used a time step of 0.01 s. In theory, this could mean that the video analysis could take up to 150 hours per participant, which is not feasible.

The optical motion capture system relies on the markers being visible and if one is obstructed for a short period of time, it tries to interpolate the position from the last time it was observed to when it becomes visible again. However, in some cases the marker is lost completely, or it starts displaying unreasonable positions. When performing a video analysis, the researcher is checking the position each time step, so if a marker becomes obstructed the researcher can try and estimate its position either by a qualified guess or, if the test has been recorded from both sides, look at the other video. The risk of losing a test because of an obstructed marker is then almost non-existent for the video analysis. Furthermore, an advantage with the video analysis method is that areas not fitted with markers can be observed and possibly analysed as well, while the optical motion method only captures the markers.

The optical motion capture system has a limit on how many markers can be used at the same time, the system used in this thesis had a cap of 36 markers, while a newer system was found to have an upper limit of 56 (Charnwood Dynamics Limited). This restricts the researcher in how many participants can be fitted with markers and subsequently be analysed with this method, while the only thing that might restrict the number of markers for the video analysis method is the time required to attach them. Utilising Codamotion in an experiment such as the Lund experiment is still possible, but it would only track a few peoples' movement and miss out on the entire groups' individual variations.

There is no real difference in user-friendliness between the two methods. Both have preparations prior to the start of the experiment that, although different, aren't difficult to do. Regarding eye tracking, it would be possible to combine that equipment with the motion capture system. However, without enough markers on the person walking in front and on the person wearing the eye tracker, it would be hard to synchronise the two recordings afterwards. It is much easier to combine it with the video analysis method.

The list presented in section 1.1 has 22 parameters that affect the movement of crowds. Some of these parameters can be considered as pre-conditions to an experiment, and not the actual measured parameter. Age for example, the experiment can be conducted with groups of different ages, but the difference would build on measurements of e.g. step frequency or lateral sway, meaning that if the step frequency can be measured, the effect age has on crowd movement can be established as well. The parameters have been divided into "Direct" and "Indirect" categories, where the definition of indirect is built on the "Age" example, see Table 8.

Table 8 - Parameters highlighted by Hansen (2018) divided into direct and indirect categories.

Direct	Indirect	
Step frequency	Age	Health status
Step size	Height	Fatigue
Headway/inter person distance	Fitness	Vision
Lateral sway	Culture	Bottlenecks, openings
	Weight	Stair gradient
	Social relations	Personal space
	Emotional state	Body projection area
	Gender	Group size
	Emergency or non-emergency	Occupant density

The "Direct" parameters can all be measured by utilising either one of the video analysis method or the motion capture method. The Step frequency, step size and headway/inter person distance can all be derived from the graphs presented in section 5.1. Lateral sway would have to be measured from above with the video analysis method, which has already been done by Cao, et al (2016). It would be possible to do with the optical motion capture method as well, as long as a marker on top of the head is visible. Parameters that aren't mentioned in the list, such as velocity or step overlapping, can be measured as well as evident in what was presented in 5.1.

To summarise, it is possible to measure all the parameters presented by Hansen (2017) with both analytic methods. Table 9 shows the advantages and disadvantages that has been identified in this discussion.

Table 9 - The advantages and disadvantage of the two methods conducted

	Video Analysis	**Optical motion capture**
User friendliness: Preparation	High	High
User friendliness: Collection	High	High
User friendliness: Analysis	High	High
Economical aspect	Cheap even if you have to invest in the hardware	Expensive if you have to invest in the hardware
Data accuracy	It depends on the chosen sampling rate	High, the sampling rate is 100 measurements per second
User dependency	High, everything from the collection to the analysis has user dependant aspects	Low, only the preparation has user dependant aspects
Can be combined with eye tracking	Yes	Yes, but a comparison between the data will be difficult
Can handle obstructed markers	Yes, but the markers' positions will be estimated by the researcher	Yes, but only if they are obstructed for a short time
Can analyse other areas than those that have markers	Yes, however the accuracy will be lower compared to the marked areas	No
Can be used for a realistic crowd investigation	Yes, however the accuracy of the results would be negotiable	No, markers would be obstructed for too long
Time consuming: Collection	It depends on how many participants you have and how many tests are needed	It depends on how many participants you have and how many tests are needed
Time consuming: Analysis	Yes, even if the analysis is automatic	No, the analysis is completed during the experiment

6.3 Future work

The results presented in this thesis has been derived from a small part of the data that was collected during the experiments. One of the goals of this thesis was to create a database on which further research could be conducted. Therefore, there is a lot of data that can be investigated and in this section we want to present what we believe is the next step in this area of research.

Since the motion capture method has a high sampling frequency and is much faster at producing data, compared to the video capture method, this is a good starting point. It would be relatively quick to go through all the data that the Codamotion system generated. It is then possible to see if the indications presented in this thesis are correct, or if they need to be adjusted. Following this, a comparison between the ordinary walking tests and the sudden-stop tests can be performed as this will show if people change their preferred distance towards the person walking in front when they have become aware that a potential sudden stop might occur. The tests where we walked as a group could be looked at as well, however it is unclear how much data is useable. It might be necessary to compare this with the recordings from the video camera that was used to document the Dublin experiments.

The next step is the inertial sensors. We did not analyse any of the data from them due to a limited timeframe, but it is clear that they have a lot of potential. It would be interesting to see if it is possible to calculate the inter person distance with the data from the inertial sensors. Furthermore, considering that they were combined with the motion capture system, there is an opportunity to compare the data in order to check their validity. If it is indeed possible, they could be used in more realistic scenarios e.g. they could be attached to people that are attending a conference and then record data in a staged evacuation. Since the sensors are small and inconspicuous, they could be described as something else when attached to the attendees of the conference.

Although it would require considerable amounts of time, there is a lot of material from the video capture experiment that can be analysed as well. Firstly, all the tests could be analysed as we did using two random people, one walking in front of the other, to see if the indication that the relationship between inter person distance and step length, in relation to velocity, is indeed logarithmic as we showed there being indications of. This relationship is worth investigating further as it might conclude that measuring the inter person distance is sufficient and that the step length could be derived from that.

We did both single file and double file tests, and the double file tests could be analysed in order to investigate the same parameters that we looked at, both in relation to the person in front, but also in relation to the adjacent file. The data from the eye tracker could be combined with the video data as well, this would enable us to look at how the eye movements change at certain events, e.g. a sudden stop. However, we suggest that some time should be spent on finding a more suitable image processing software than we used.

Since we showed that similar walking speeds during tests with different preconditions produced the same inter person distance, we would recommend going through all the tests from the Dublin experiment and create a inter person distance against velocity chart and see what kind of relationship can be found. Following this, an analysis of the data from the Lund experiment could be conducted on all of the tests, using the same process of analysis that we used. The results from this analysis can then be compared with the inter person distance against velocity chart to see if the chart can predict the inter person distance. If it can, this would be a much stronger indication that data collected during test with a few people can be applied to larger crowds.

7 Conclusion

The parameters that were presented by Hansen (2018) were divided into direct and indirect parameters and it was established that both the traditional video analysis method as well as the more modern motion capture method can be used to measure all of these parameters. The data collected during the experiments can be used to investigate the direct parameters, as well as the height, body projection area and occupant density. Culture and emergency or non-emergency could possibly be investigated as well, however this needs a new experiment where these indirect parameters are varied. If one method is better than the other is hard to decide, but in the end the motion capture method seems to be more favourable to use in future experiments regarding crowd movement. By establishing this, a step forward has been taken when it comes to improving assumptions in evacuation simulators.

The two tests that were analysed showed no major differences between each other regarding the measured inter person distances, contact distances and step lengths. In fact, a possible relationship between inter person distance and step length, in relation to velocity was found. Furthermore, the average inter person distance was shown to be the same in the two tests even though the available space towards the person in front was governed by the occupant density in one test, and personal preference in the other.

Combining the video analysis method with an eye tracking study did not affect the results in any way, and it helps to understand the decision-making that occurs when people move through crowds. The results from the analysis indicates that there is a difference between what taller and shorter people look at when moving in high and low occupant densities. A summary of the conclusions regarding what people look at while moving through a crowd are as follows:

- Taller people generally look more at the head and neck and at the second person in front of them.
- Shorter people generally look at the head and neck as well, but they tend to look at the shoulders, as well as the back, of the people in front more often than taller people. Furthermore, they tend to look at the first person in front of them.
- During higher densities, people look at the head, neck and shoulders almost entirely and they focus mostly on the second and third person in front of them.
- During lower densities, people are focusing on more areas than during the higher densities, but it is most often on the head, neck and shoulders. Mainly, it is the first person that is looked upon.

However, further research is needed for both the optical analysis methods and the eye tracker. The vast amount of data collected meant that only a small portion could be analysed during this thesis. It would be interesting to see what an in-depth analysis would yield and if this could be implemented in and improve current egress simulation models. As for the inertial sensors, if the results are comparable with the motion capture results, the next step would be to test them out in a situation that is more anchored in reality.

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Appendix A

Reaction time – ruler drop test

To measure the participants' reaction time, a ruler drop test was utilised. This test has been shown to be acceptable for clinical use (Eckner et al., 2015). It can be useful to compare the reaction times with the inter person distance during the second set of tests in the Dublin experiment, where the leader suddenly stops, to see if there is a connection between the reaction time and the possible increase in inter person distance compared to the first set of tests.

As the name suggests, the reaction time is calculated with the help of a simple ruler. The test assumes that the participant will catch the ruler as fast as they can. The participant lays their arm on a table so that the hand protrudes over the edge. The instructor holds the ruler so that the '0' sits between the participants thumb and index finger at a distance of 2cm towards each finger. The participant is asked to focus their gaze on the '0' and catch the ruler when it drops. When it is done, the instructor checks how far the ruler has dropped uses the distance to calculate the reaction time using the following equation.

$$S = \frac{gt^2}{2} \leftrightarrow t = \sqrt{\frac{2s}{g}}$$

Where

g = 9.81	[m/s^2]
S = distance	[m]
t = time	[s]

Appendix B

Walking speed

This appendix describes the motivations for the speeds that were chosen for the motion capture experiment performed at UCD in Dublin, Ireland.

Walking speed depends on many factors, one of them being density. When there is sufficient space it is easy to move quickly and with a normal gait. As the inter person distance decreases, movement becomes more and more limited and when people are walking very close to each other they can only shuffle around slowly (NFPA, 2002). Other factors that can determine the walking speed are age, length, gender, culture etc. But also, the environment effects the walking speed. Franêk (2013) wrote in an article that the environment has a statistically significant role in the pedestrian walking speed. The walking speed is for example higher in areas without vegetation and with more traffic, noise and people, compared to areas with more greenery, less traffic and fewer (Franêk, 2013).

A mean walking speed is almost impossible to estimate because of this, but there has been research of different papers regarding the preferred walking speed around the world, conducted by Daamen & Hoogendoorn (2007) who compared these papers and concluded a mean walking speed to be 1.34 m/s (Daamen & Hoogendoorn, 2007). The mean, unhindered walking speed during the experiment conducted in Lund was measured to be 1.28 m/s. From these two values a “normal” speed of 1.30 m/s was chosen for the experiments.

Pedestrian walking speed at a bus terminal was studied by Mohamad Ali et al. (2018). They came to the conclusion that the mean walking speed without baggage is 1.13 m/s for men and 1.07 m/s for women. When carrying baggage, the speed is reduced to 1.02 m/s and 0.7 m/s respectively (Mohamad Ali et al., 2018). The average walking speed from these values is 0.98 m/s, which is why 1.0 m/s can be found to be a representative value in this context.

The two lowest walking speeds chosen are 0.5 m/s and 0.2 m/s. 0.5 m/s is selected since during one of the tests in Lund, the analysed participants were moving with that speed. This gives a possibility for comparison. The lowest, 0.2 m/s, is chosen because during the experiment the participants will be able to move forward in an almost natural way, albeit very slow. This value is qualitative chosen.

Porzycki et al. (2018) conducted five evacuation experiments in a tunnel in Poland in 2016. They calculated the movement speed in three of these but since they used the same demographic in all three, the participants gained knowledge of the tunnel layout (Porzycki, Schmidt-Polończyk, & Wąs, 2018) which might have affected their movement speed. The fact that it affected their pre-movement time is clearly visible in their results. The value 1.706 m/s is the mean value of their experiment labelled “experiment 1 the evacuation tunnel”, which will be used as a fast pace movement speed.

In Table 10 a summary of the speeds chosen for the experiment is listed.

Table 10 - The speeds chosen for the experiments in Dublin, Ireland

Pace	Actual speed [m/s]
Slowest	0.2
Slower	0.5
Slow	1.0
Normal	1.3
Fast	1.7

Appendix C

In this appendix, all charts produced regarding the optical methods is presented. These are test A3 and D3 from the video capture experiment, and B1.9 and B1.10 from the motion capture experiment. D3 and B.1.9 are presented in the main body of the report as well and are described more in detail there. First the two tests from the video capture experiment are presented, followed by the two tests from the motion capture experiment. A3 is a low speed, high density test, D3 and B1.9 are tests with similar speeds, and B1.10 is a test with a high speed. Inter person distance, the interaction between the heel and toe and contact distance are presented as both absolute distance over time graphs, as well as relative distance over time graphs. Step length and stride length are only presented as absolute distance over time graphs.

Video capture experiment

This experiment was conducted in Lund, Sweden on the 17th of October 2018. Test A3 had 59 participants and test D3 had 29 participants. For a detailed description of all the participants from the experiment, continue to Appendix D.

A3

In Figure C 1 the section of the analysed area that is presented in the graphs for A3 is illustrated. The presented section is a zoomed in version of the area highlighted in grey in the bottom right corner of the graph. The reason being that it is hard to distinguish anything from the original version of the graph.

The average speed during this test was 0.05 m/s.

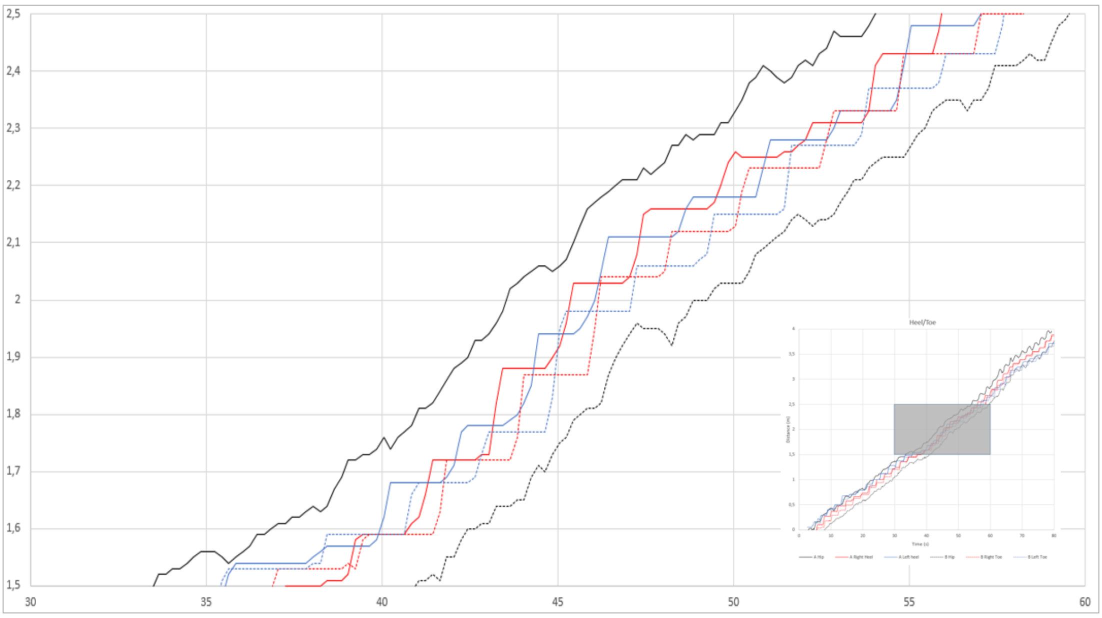

Figure C 1 - The part that shows in the charts is the grey marked area.

Figure C 2 is the absolute distance graph, and Figure C 3 is the relative distance graph regarding inter person distance for test A3.

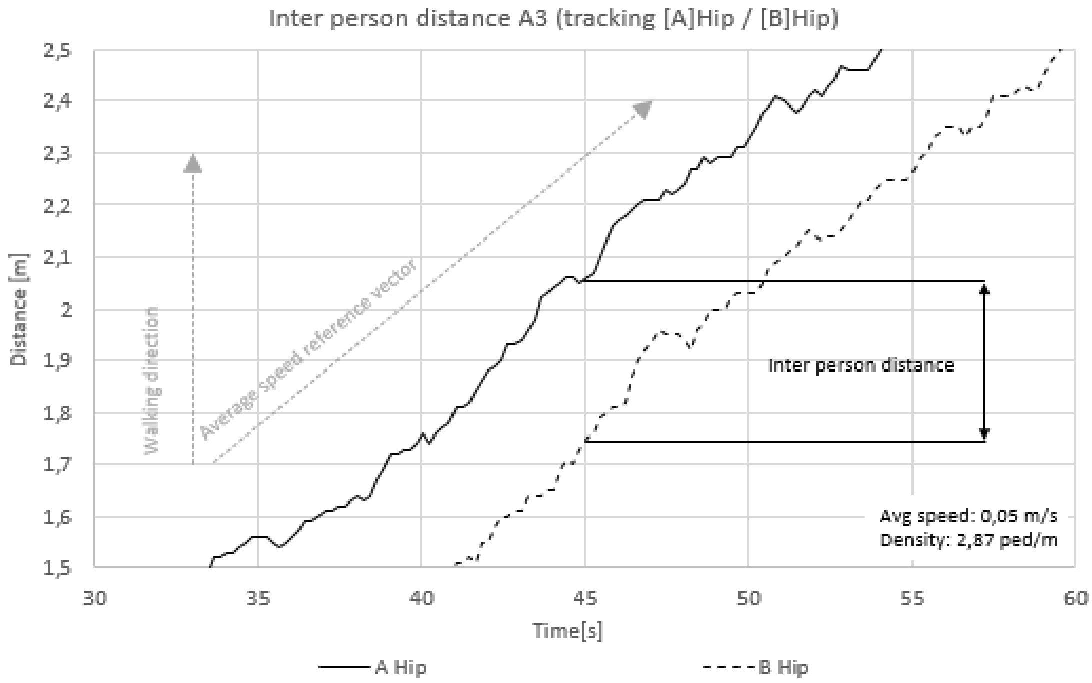

Figure C 2 - Inter person distance for test A3 from the video capture experiment

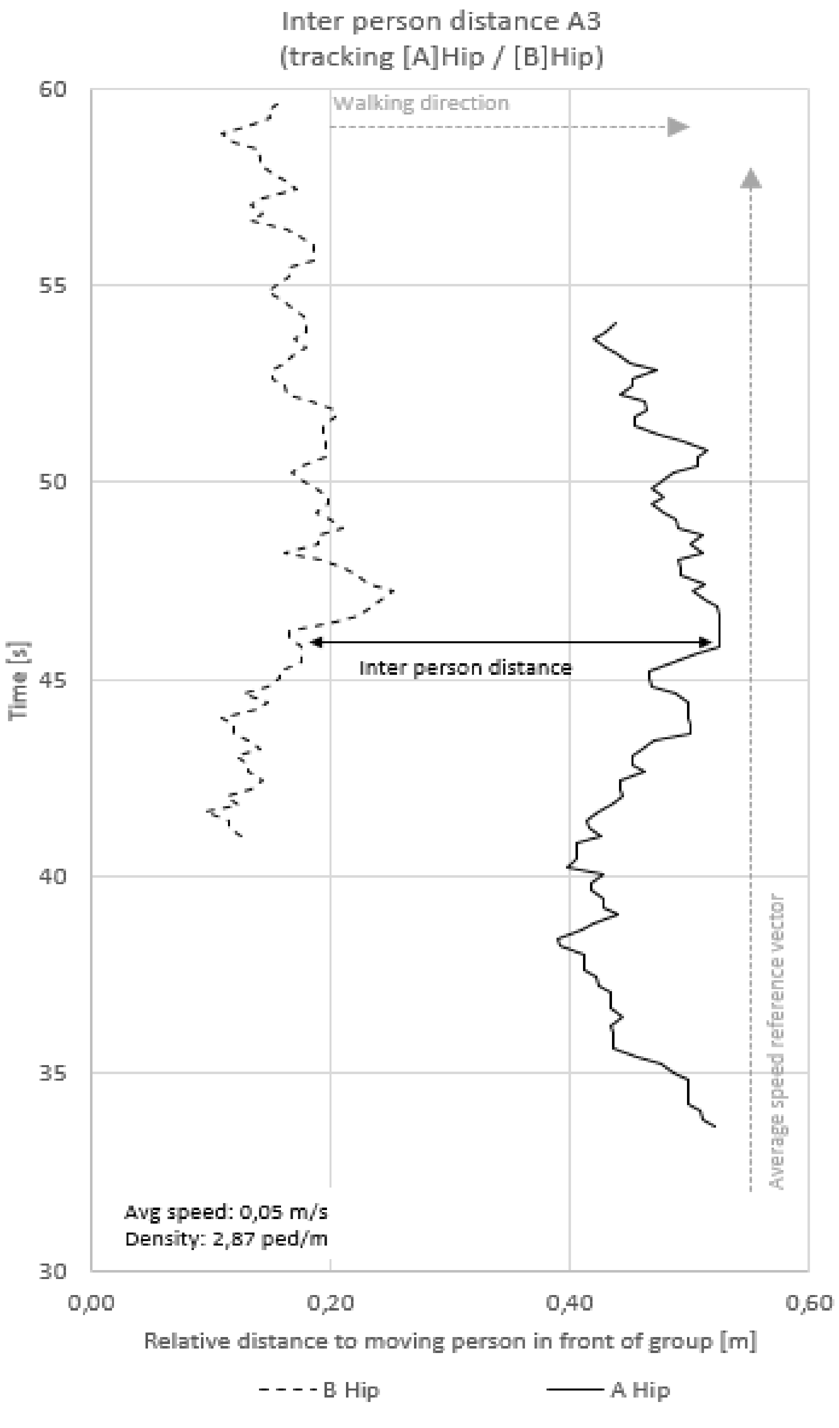

Figure C 3 -Inter person distance for test A3 from the video capture experiment, presented as a relative distance

Figure C 4 is the step and stride length for the two persons in A3.

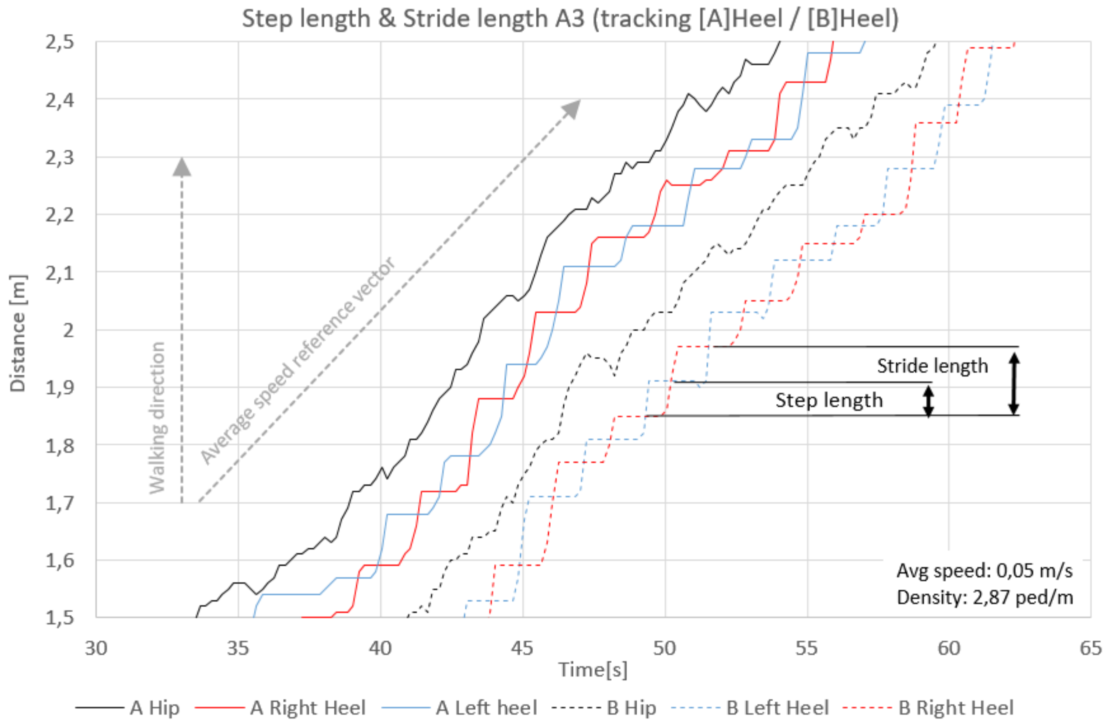

Figure C 4 - Step length and stride length for test A3 from the video capture experiment

Figure C 5 is the absolute distance graph, and Figure C 6 is the relative distance graph regarding the interaction between the heels of "Person A" and toes of "Person B".

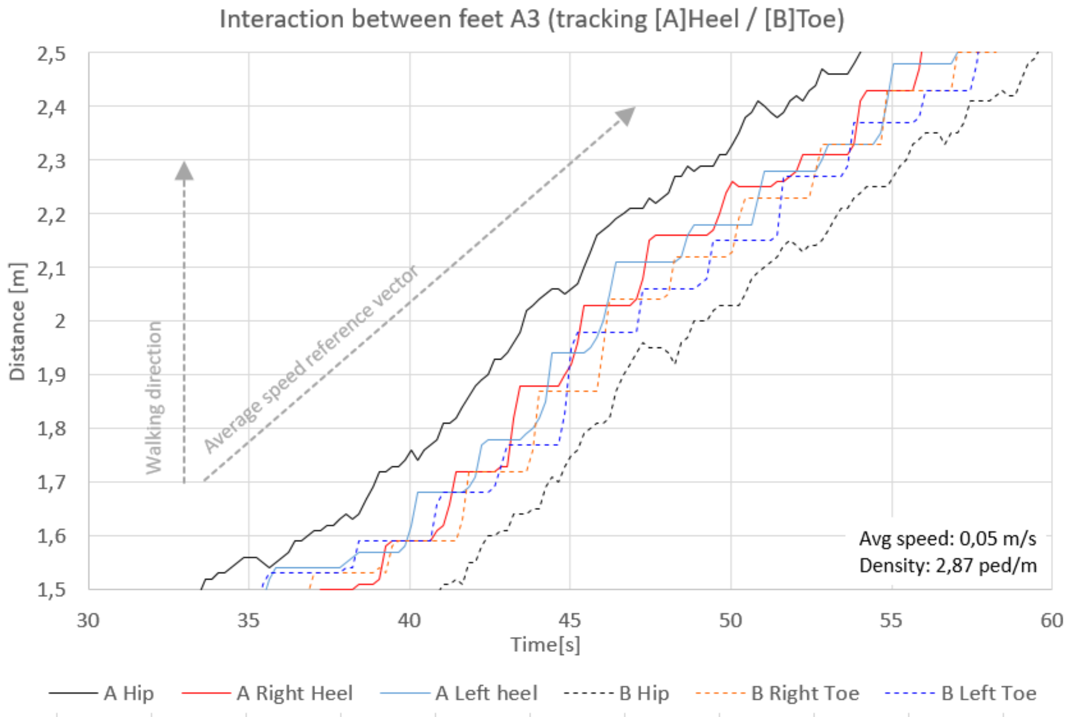

Figure C 5 - The interaction between heels and toes for test A3 from the video capture experiment

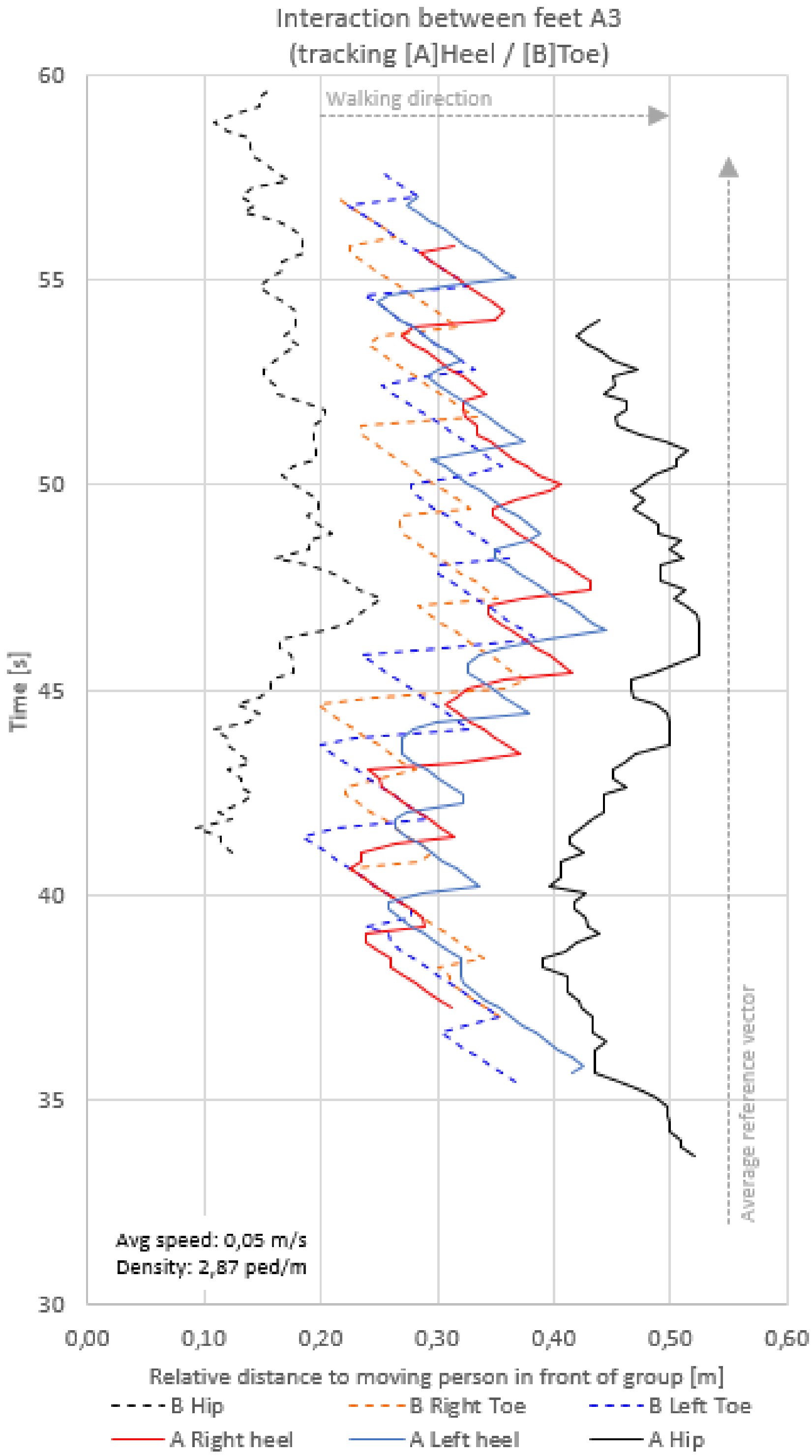

Figure C 6 - The interaction between heels and toes for test D3 from the video capture experiment, presented as a relative distance

In addition to the absolute distance graph and the relative distance graph, a graph showing the variation of contact distance over time is presented, Figure C 7, Figure C 8 and Figure C 9 respectively.

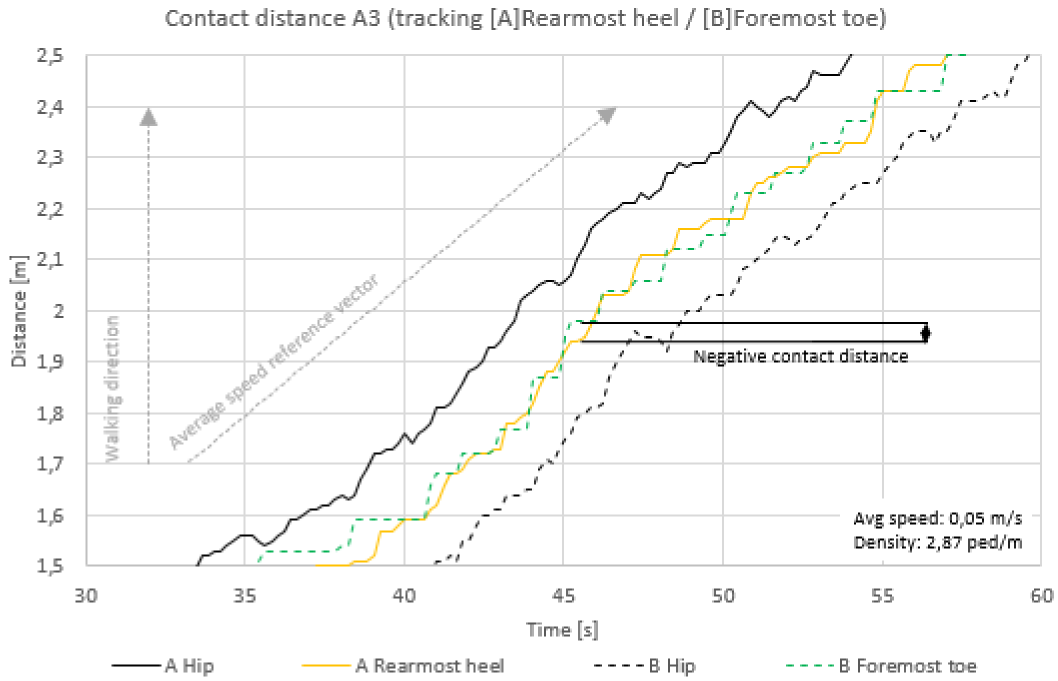

Figure C 7 - The contact distance for test D3 from the video capture experiment

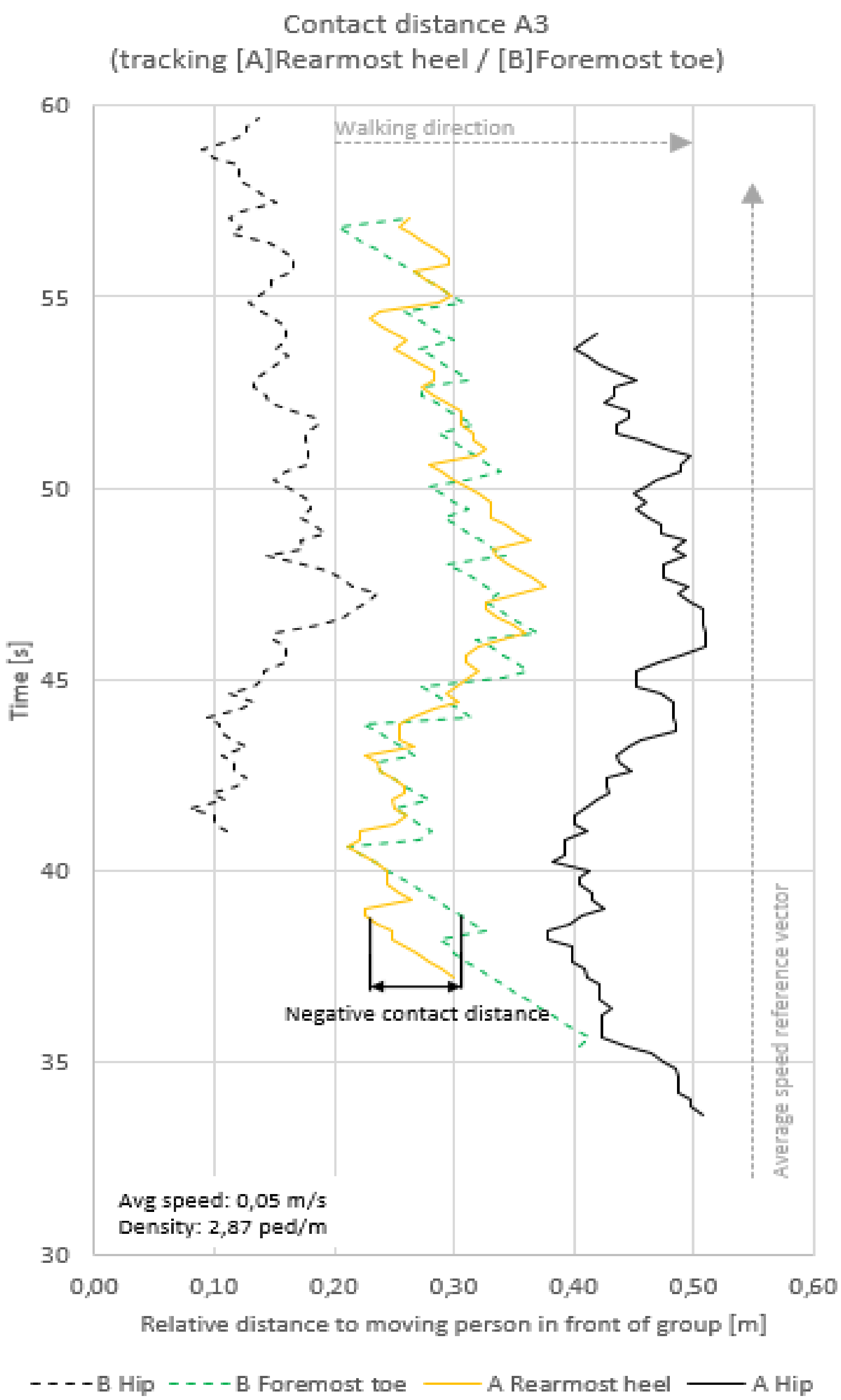

Figure C 8 - The contact distance for test A3 from the video capture experiment, presented as a relative distance

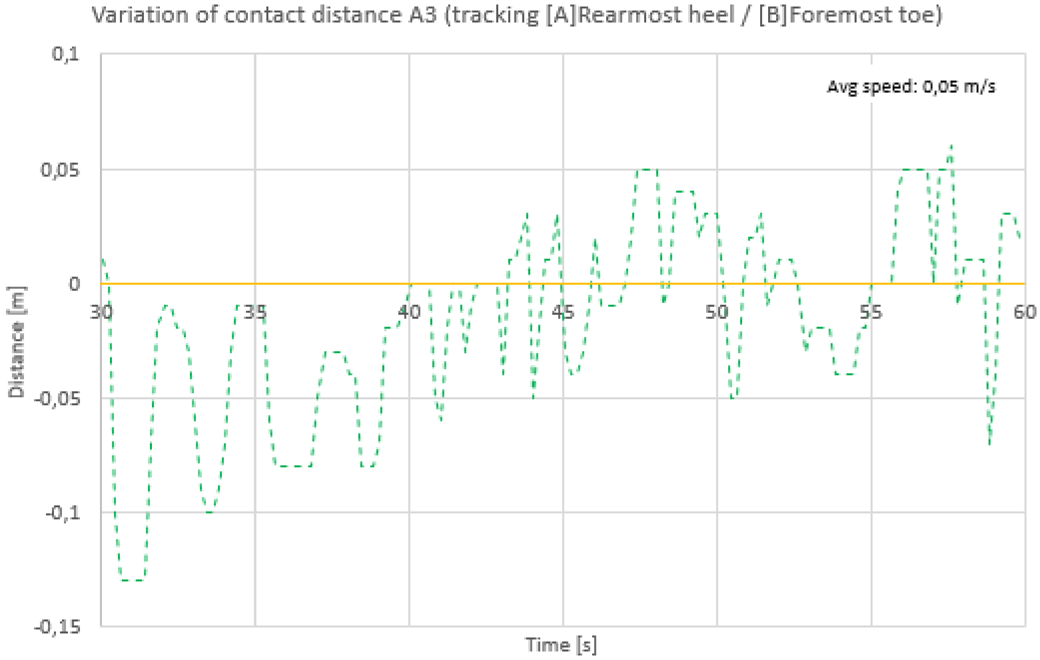

Figure C 9 - Variations of contact distance for test D3 from the video capture experiment

D3

Figure C 11 is the absolute distance graph, and Figure C 10 is the relative distance graph regarding inter person distance.

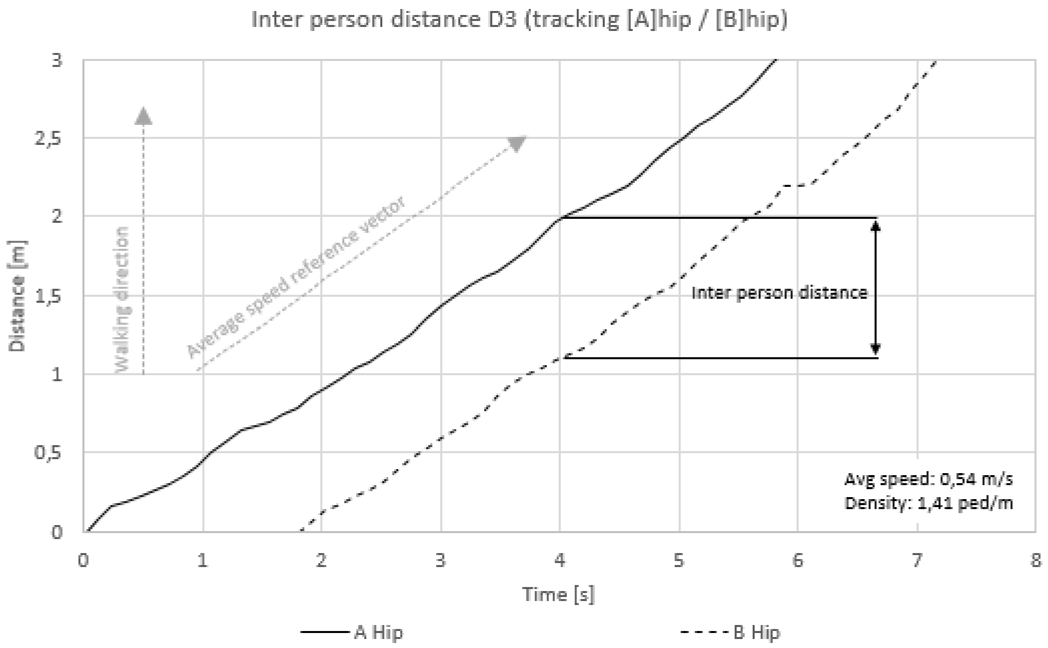

Figure C 11 - Inter person distance for test D3 from the video capture experiment

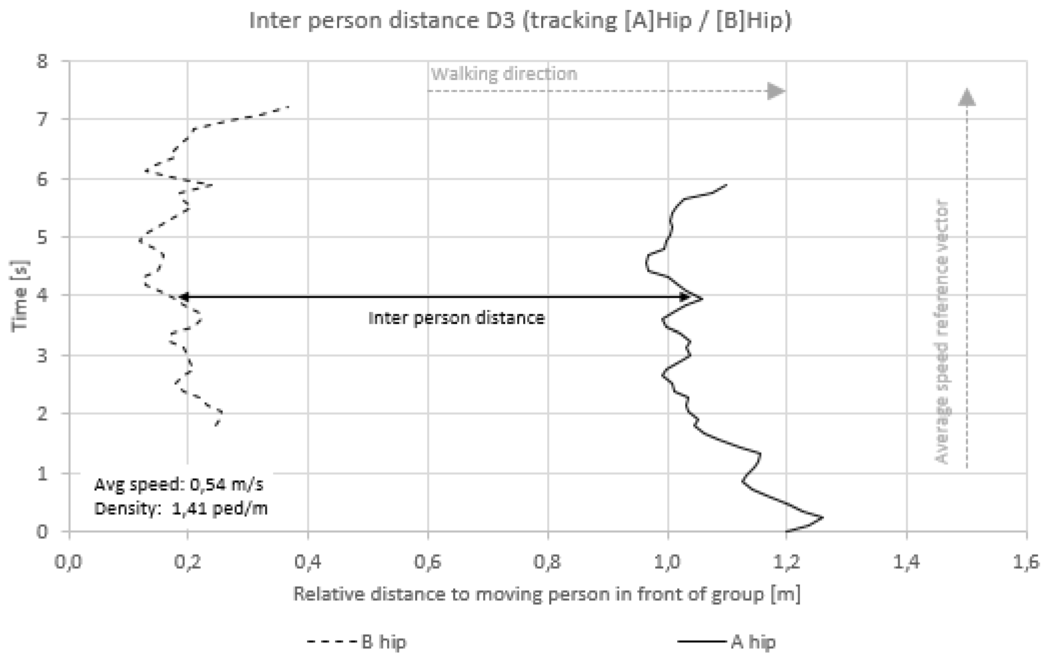

Figure C 10 - Inter person distance for test D3 from the video capture experiment, presented as a relative distance

Figure C 12 shows the step and stride lengths.

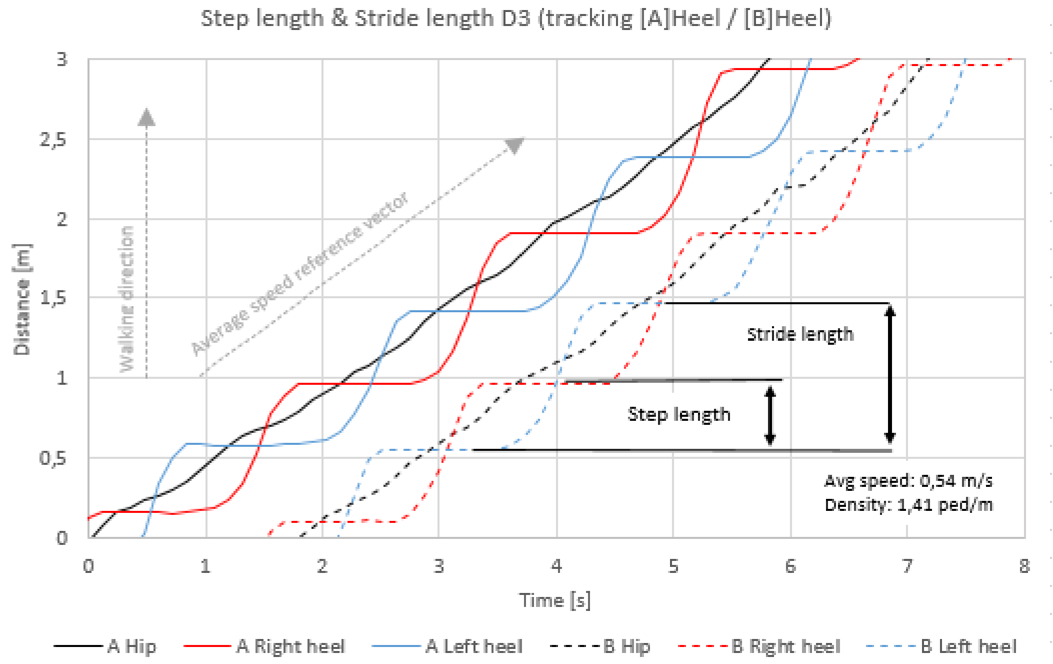

Figure C 12 - Step length and stride length for test D3 from the video capture experiment

Figure C 13 is the absolute distance graph and Figure C 14 is the relative distance graph regarding the interaction between the feet.

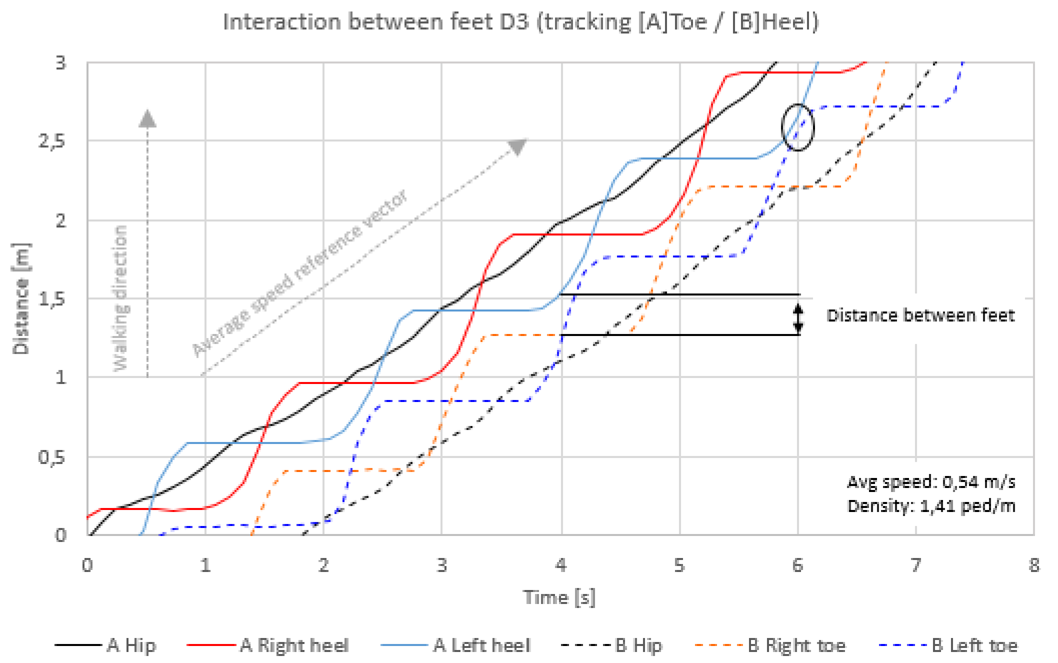

Figure C 13 - The interaction between heels and toes for test D3 from the video capture experiment

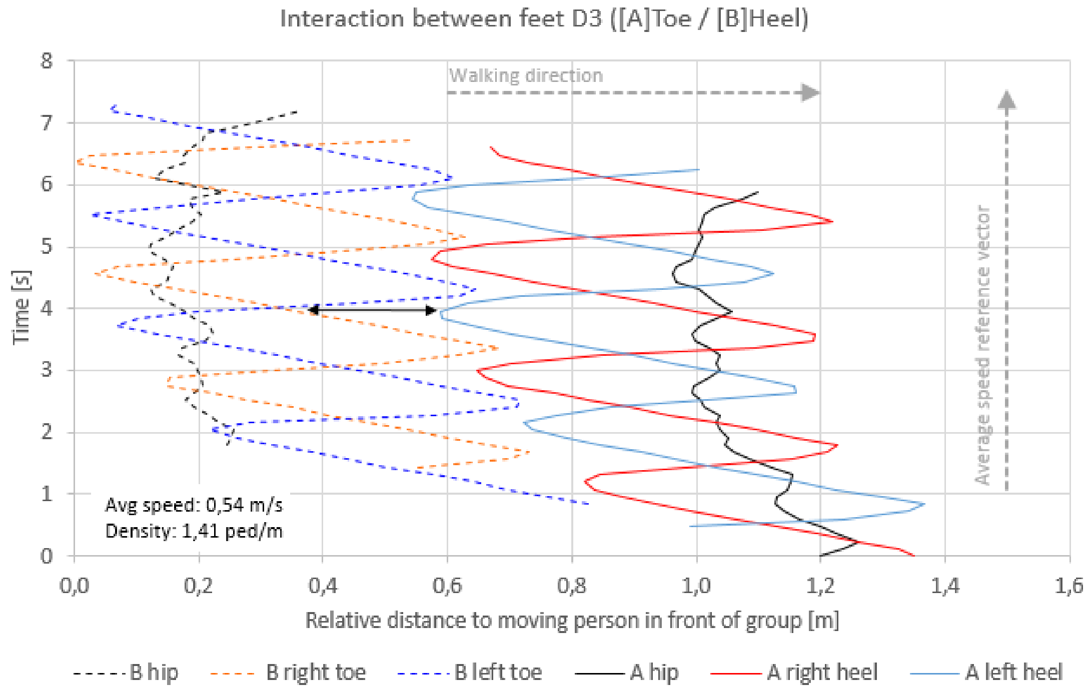

Figure C 14 - The interaction between heels and toes for test D3 from the video capture experiment, presented as a relative distance

In addition to the absolute distance graph and the relative distance graph, a graph showing the variation of contact distance over time is presented, Figure C 15, Figure C 16 and Figure C 17 respectively.

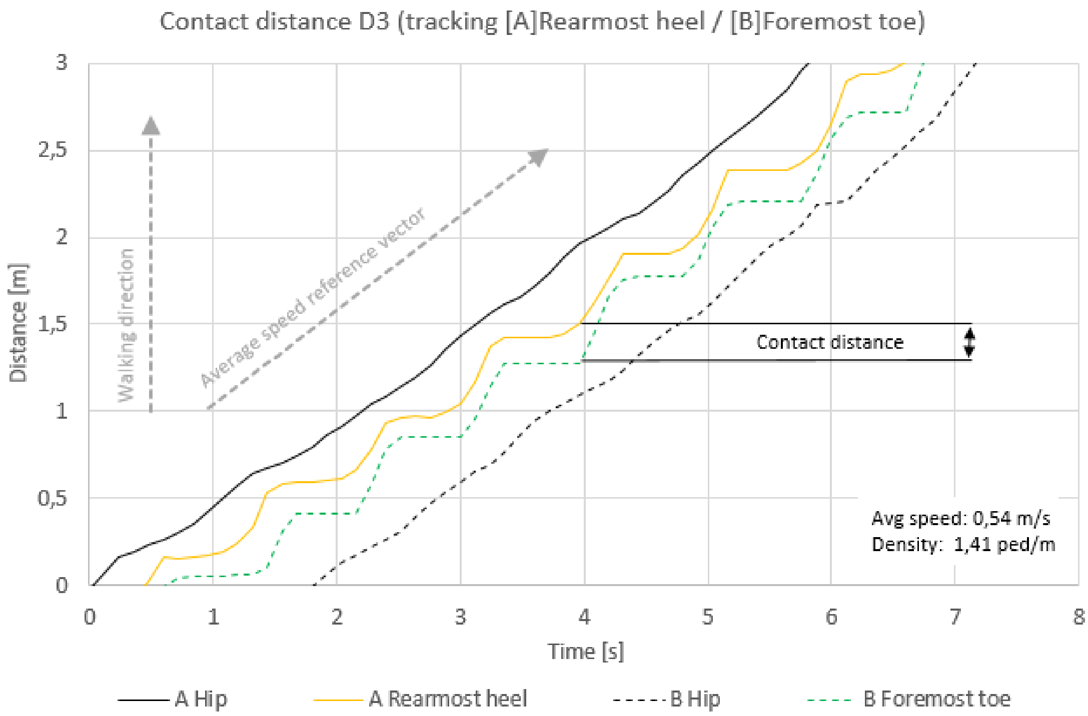

Figure C 15 - The contact distance for test D3 from the video capture experiment

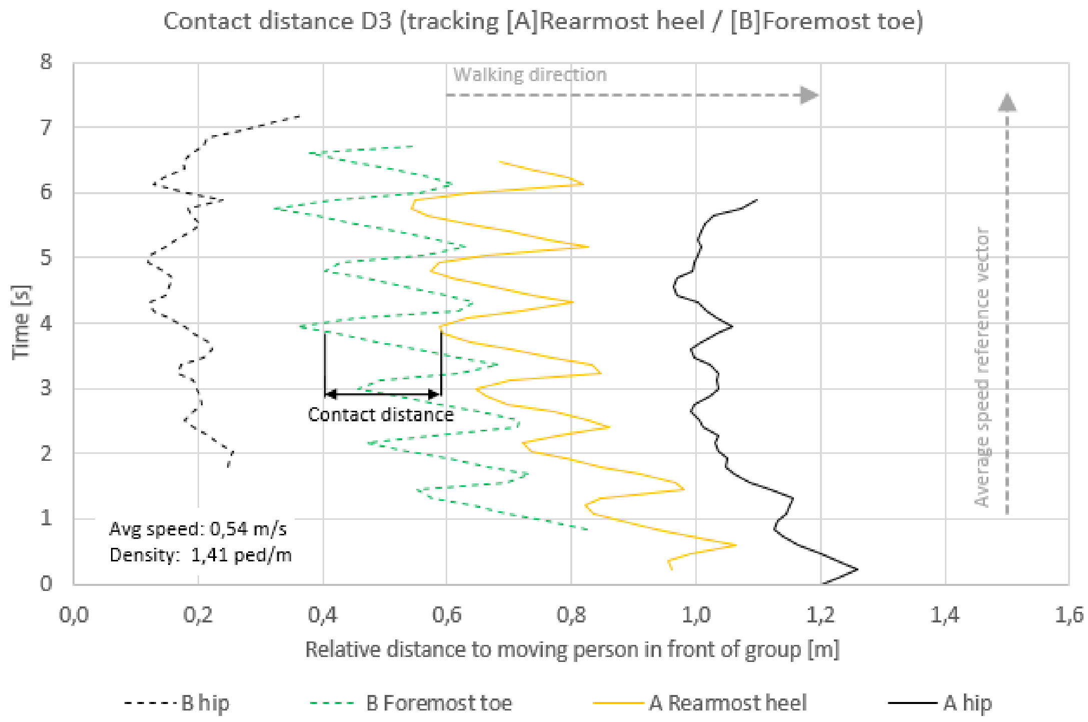

Figure C 16 - The contact distance for test D3 from the video capture experiment, presented as a relative distance

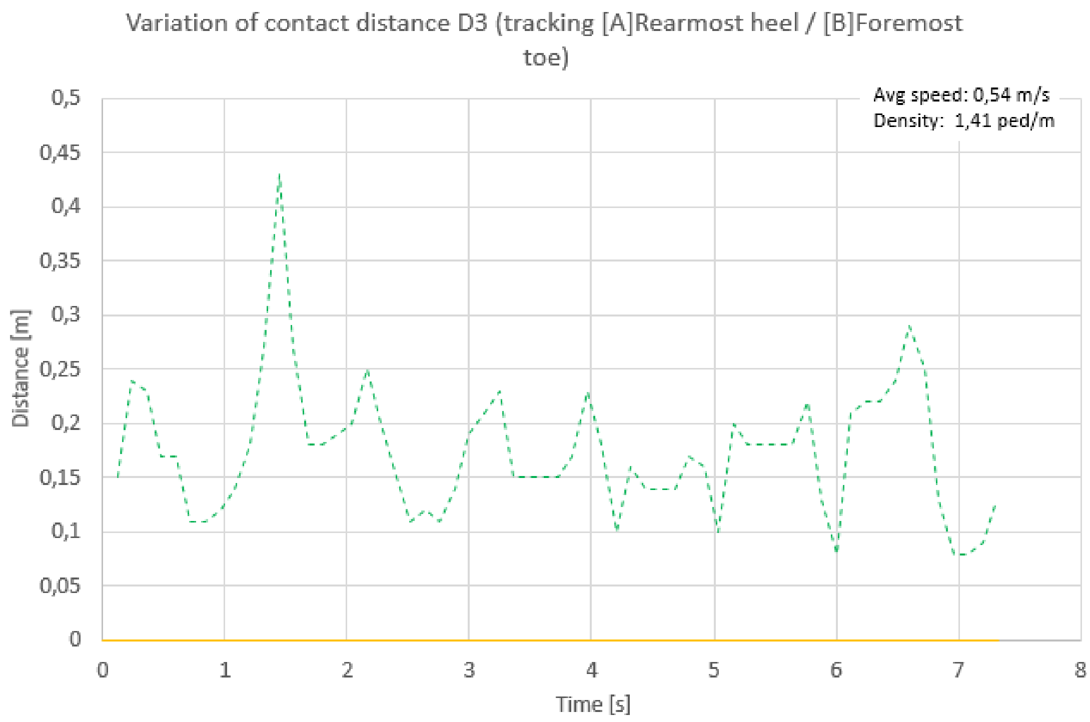

Figure C 17 - Variations of contact distance for test D3 from the video capture experiment

Motion capture experiment

This experiment was conducted at University College Dublin in Dublin, Ireland on the 4th, 5th, 7th and 8th of December 2018. Both tests had four participants. For a detailed description of all the participants from the experiment, continue to Appendix E.

B1.9

Figure C 18 is the absolute distance graph and Figure C 19 is the relative distance graph regarding inter person distance.

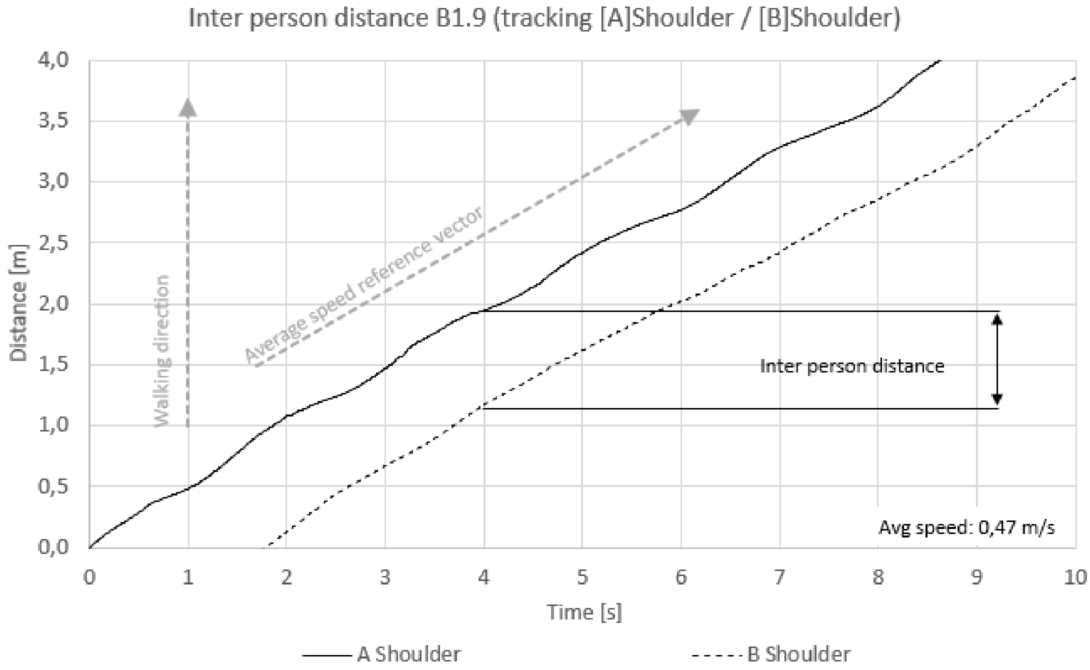

Figure C 18 - Inter person distance for test B1.9 from the motion capture experiment

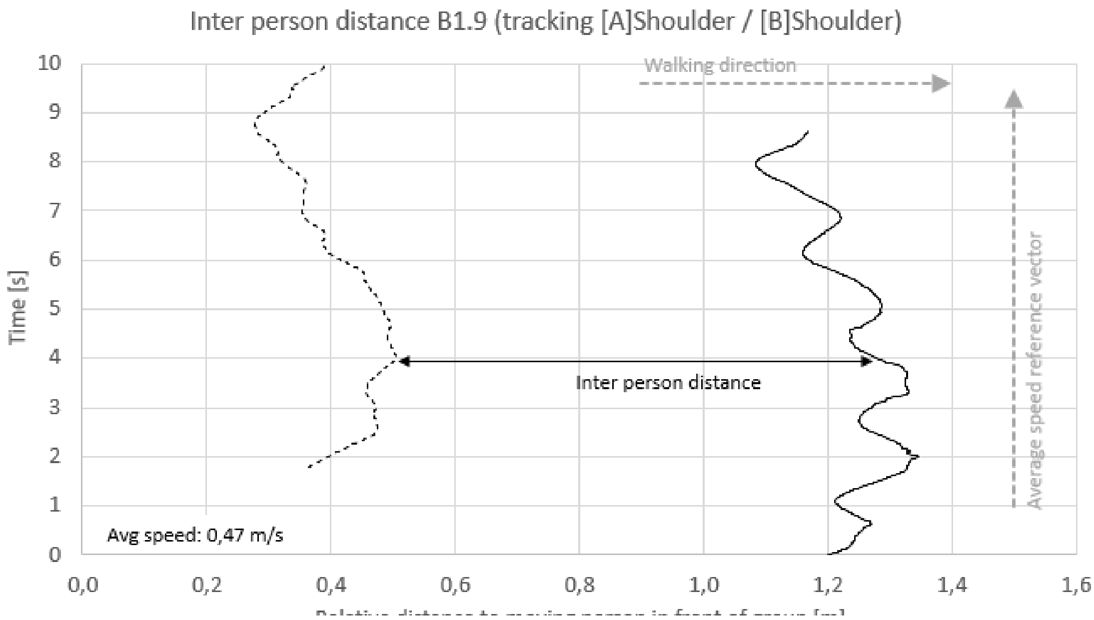

Figure C 19 - Inter person distance for test B1.9 from the motion capture experiment, presented as a relative distance

Figure C 20 shows the step and stride lengths.

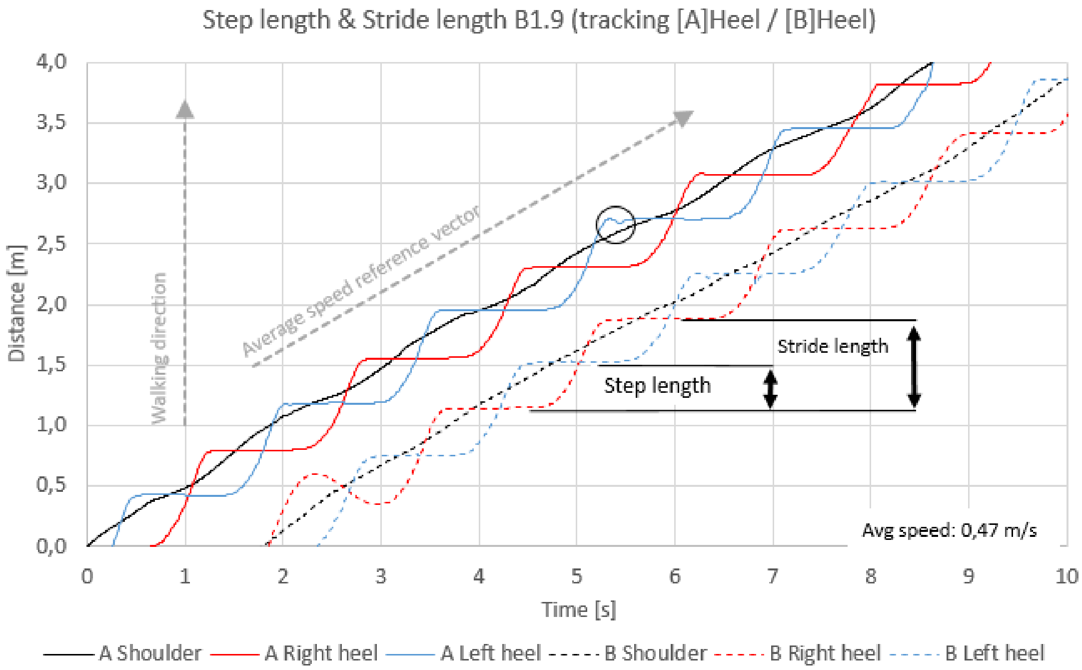

Figure C 20 - Step length and stride length for test B1.9 from the motion capture experiment.

Figure C 21 is the absolute distance graph and Figure C 22 is the relative distance graph regarding the interaction between the feet.

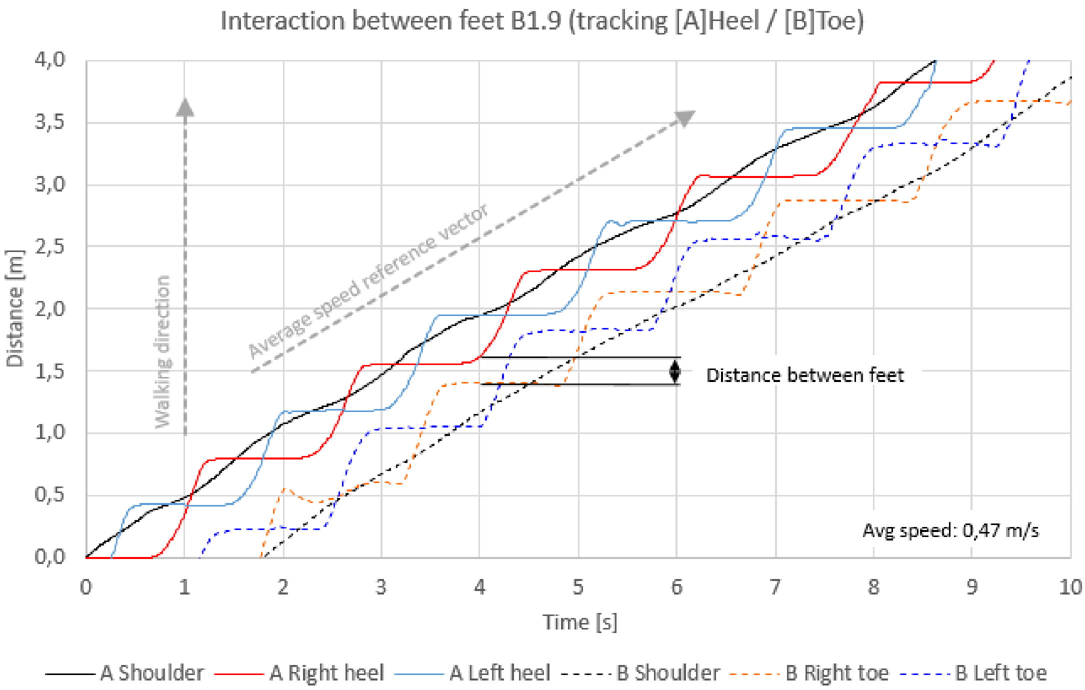

Figure C 21 - The interaction between heels and toes for test B1.9 from the motion capture experiment

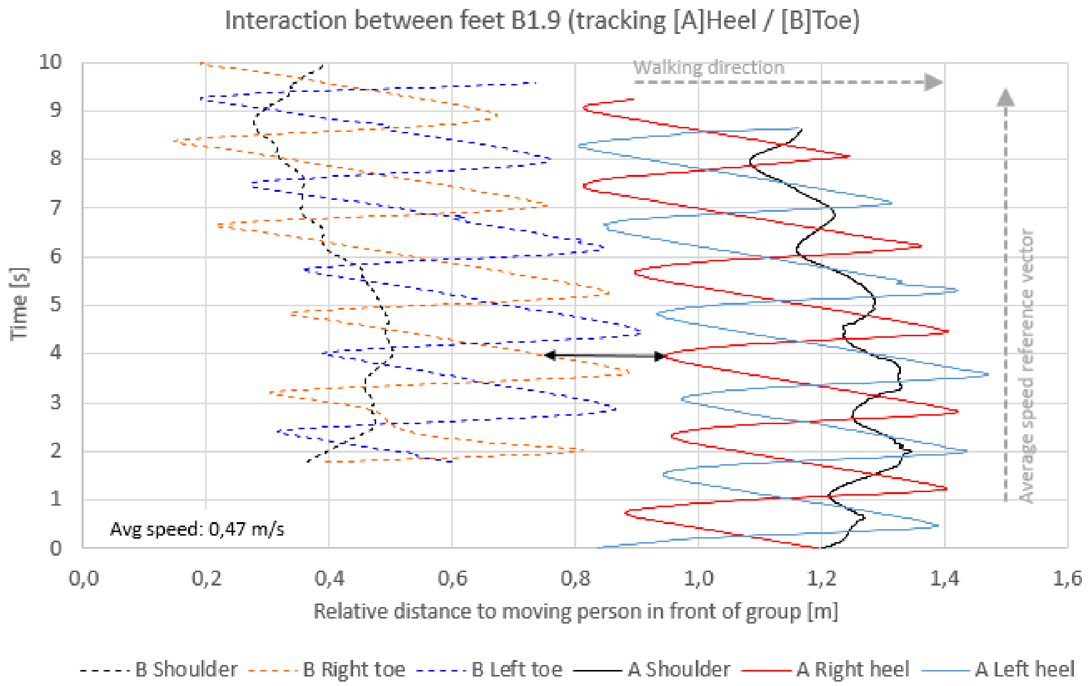

Figure C 22 - The interaction between heels and toes for test B1.9 from the motion capture experiment, presented as a relative distance

In addition to the absolute distance graph and the relative distance graph, a graph showing the variation of contact distance over time is presented, Figure C 23, Figure C 24 and Figure C 25 respectively.

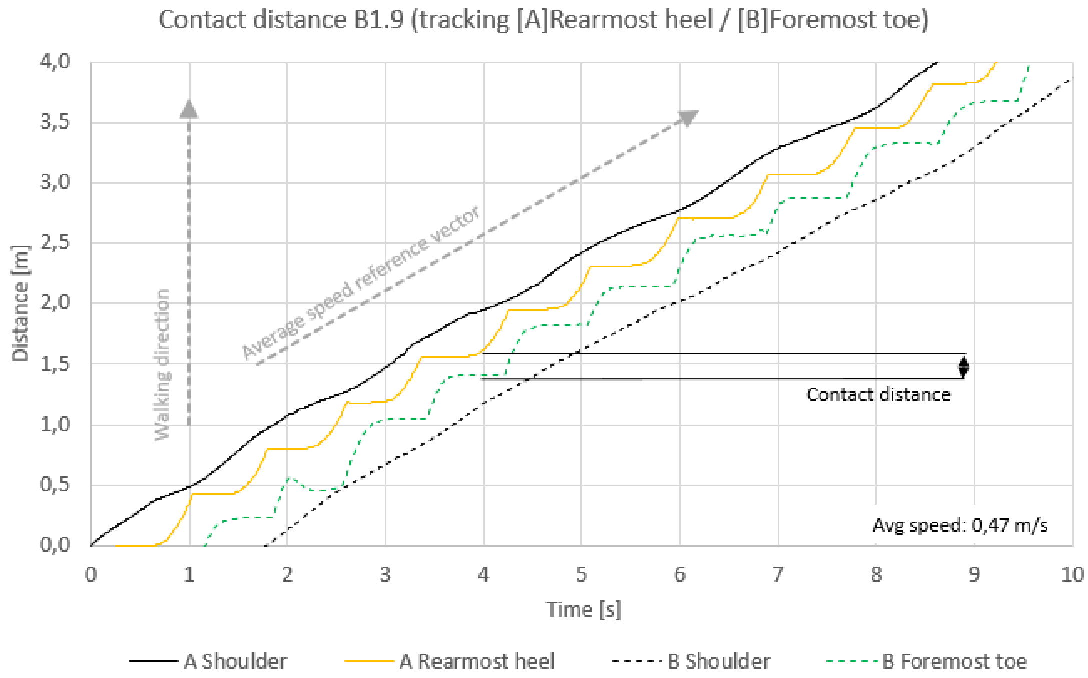

Figure C 23 - The contact distance for test B1.9 from the motion capture experiment

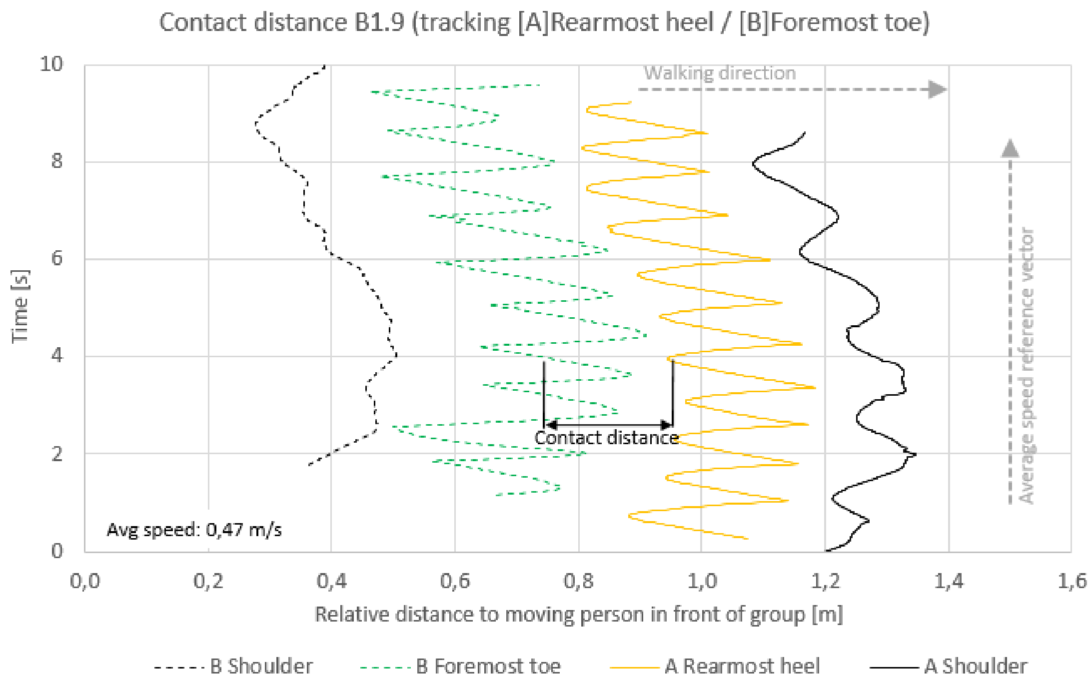

Figure C 24 - The contact distance for test B1.93 from the motion capture experiment, presented as a relative distance

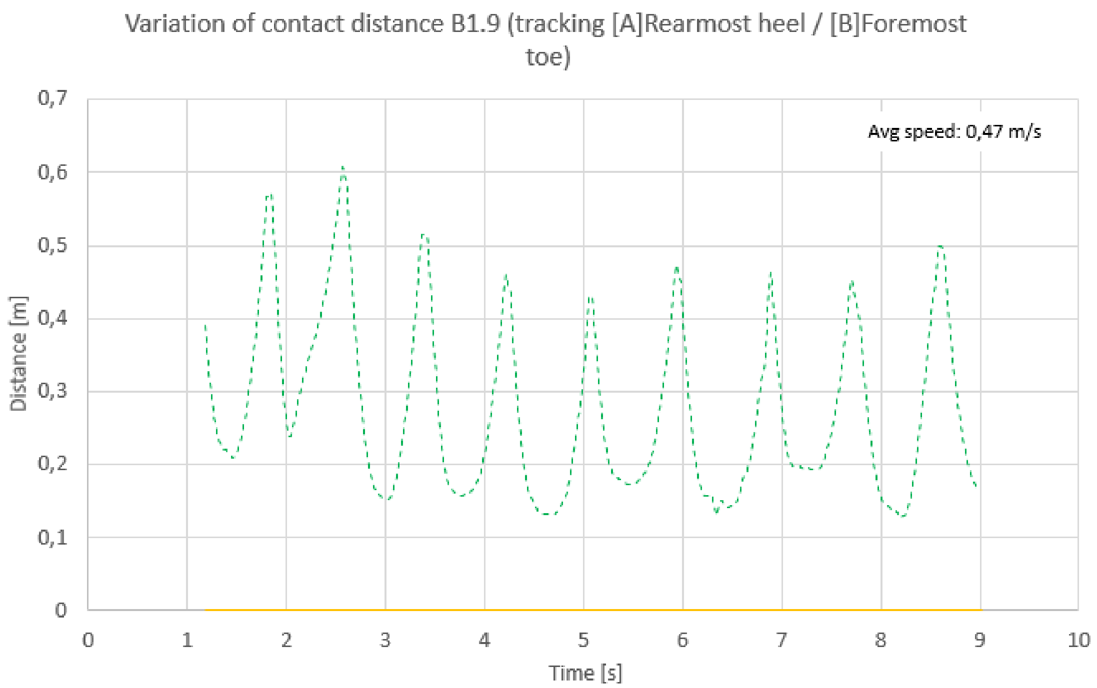

Figure C 25 - Variations of contact distance for test B1.9 from the motion capture experiment

B1.10

This test had an average speed of 1.3 m/s.

Figure C 27 is the absolute distance graph and Figure C 26 is the relative distance graph regarding inter person distance.

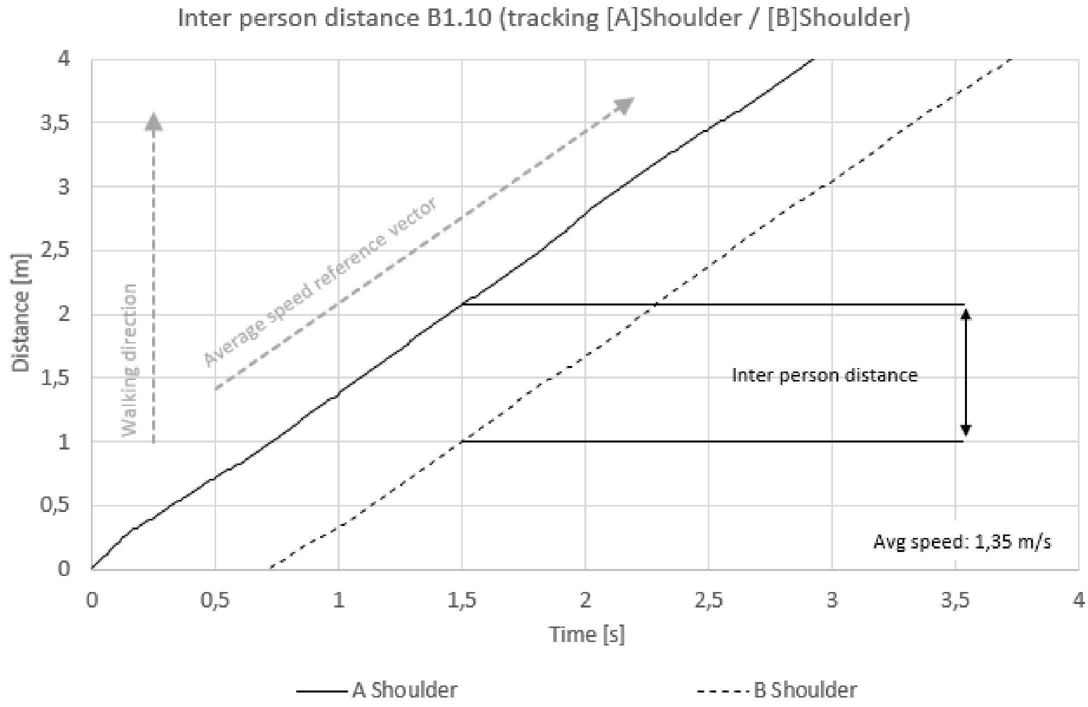

Figure C 27 - Inter person distance for test B1.10 from the motion capture experiment

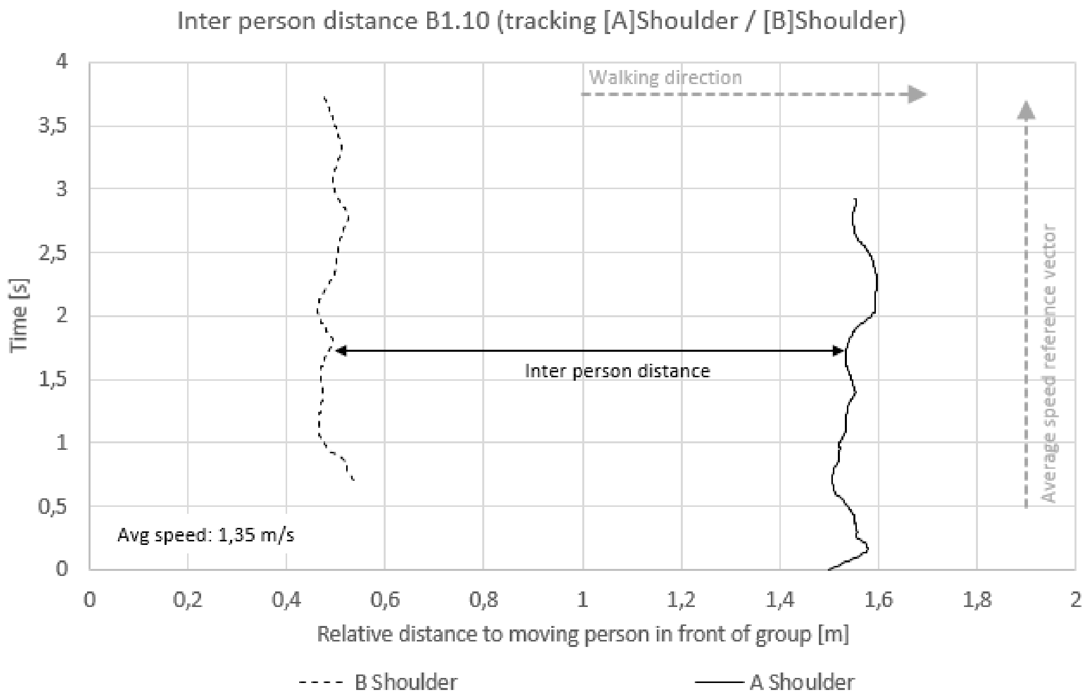

Figure C 26 - Inter person distance for test B1.10 from the motion capture experiment, presented as a relative distance

Figure C 28 shows the step length and stride length.

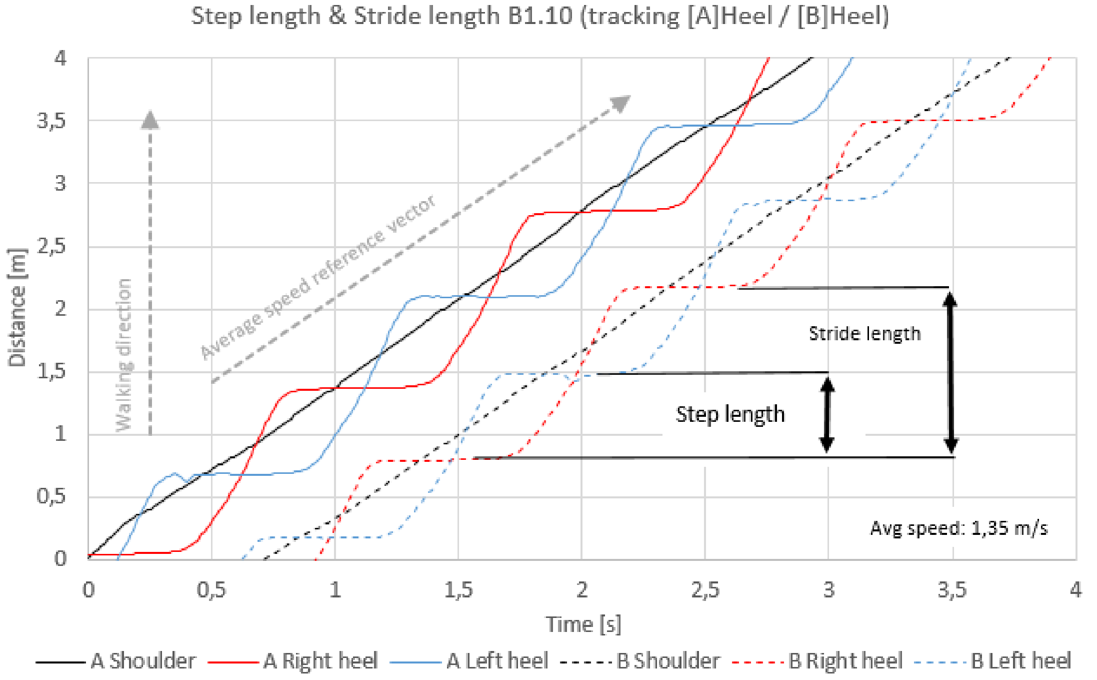

Figure C 28 - Step length and stride length for test B1.10 from the motion capture experiment.

Figure C 29 is the absolute distance graph and Figure C 30 is the relative distance graph regarding the interaction between the feet.

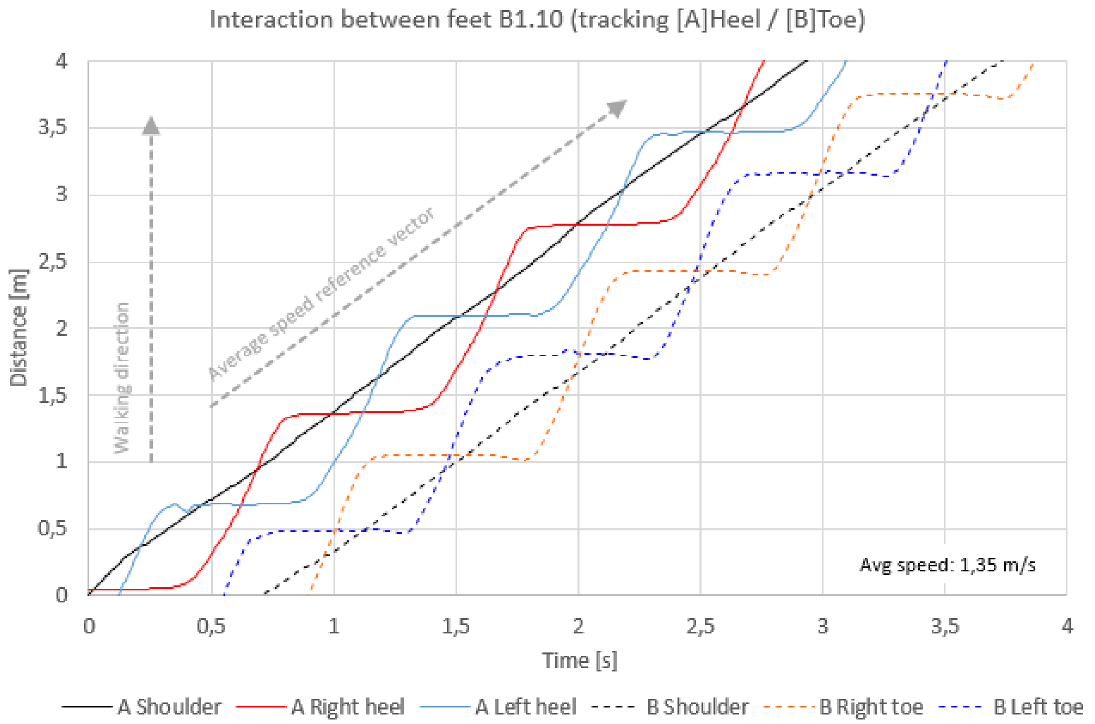

Figure C 29 - The interaction between heels and toes for test B1.9 from the motion capture experiment

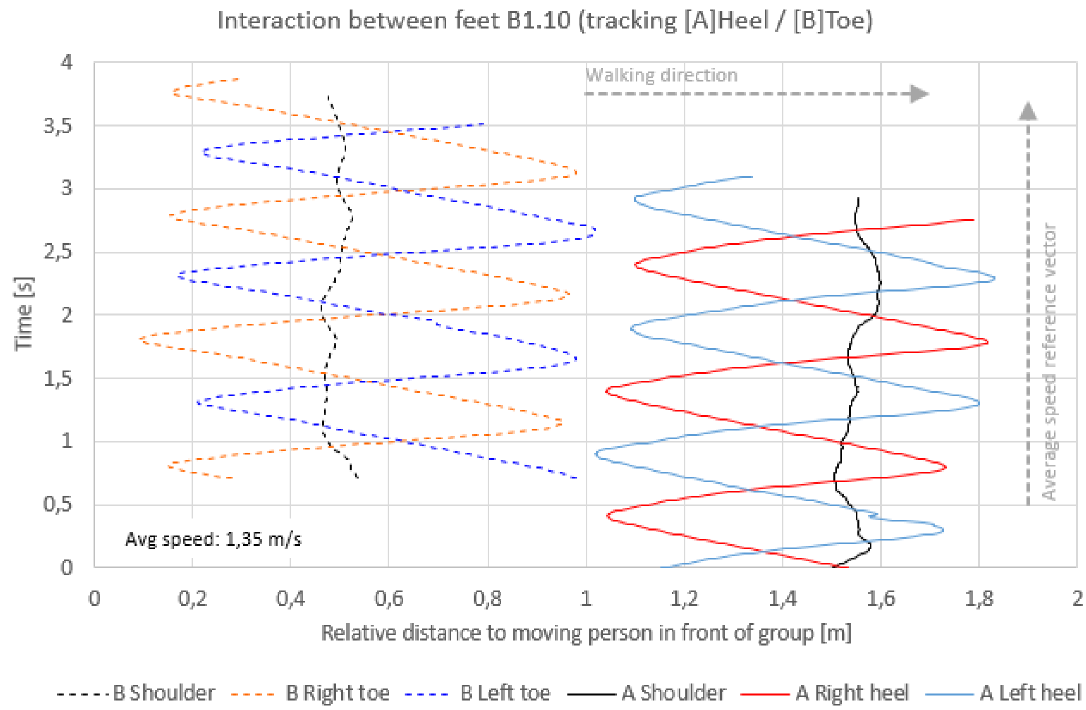

Figure C 30 - The interaction between heels and toes for test B1.10 from the motion capture experiment, presented as a relative distance

In addition to the absolute distance graph and the relative distance graph, a graph showing the variation of contact distance over time is presented, Figure C 31, Figure C 32 and Figure C 33 respectively.

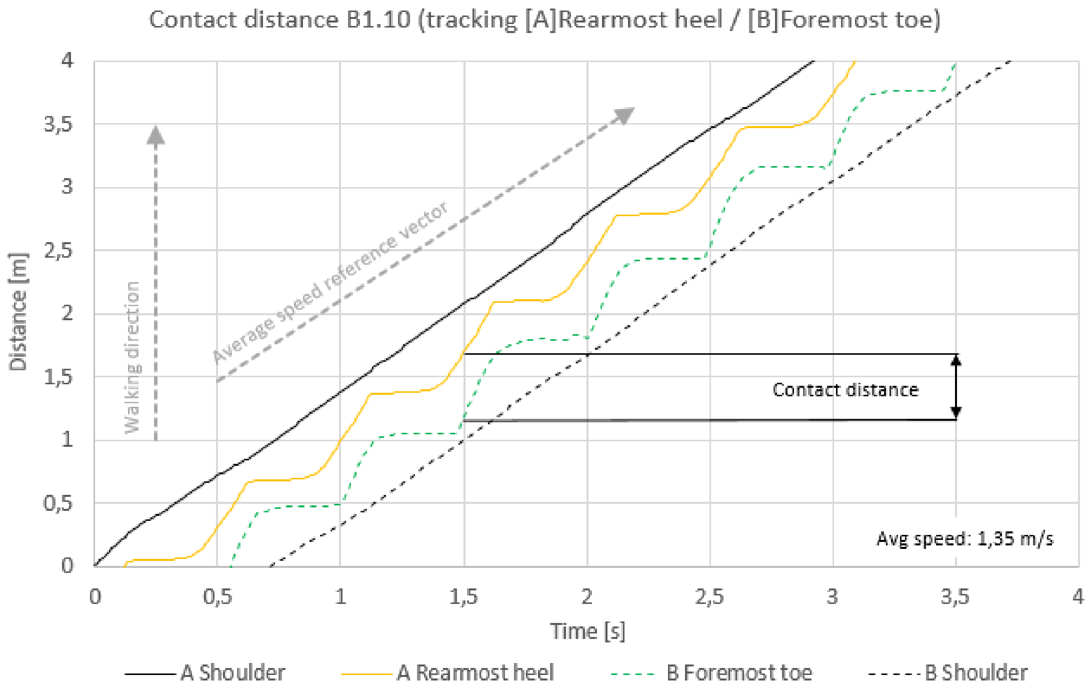

Figure C 31 - The contact distance for test B1.10 from the motion capture experiment

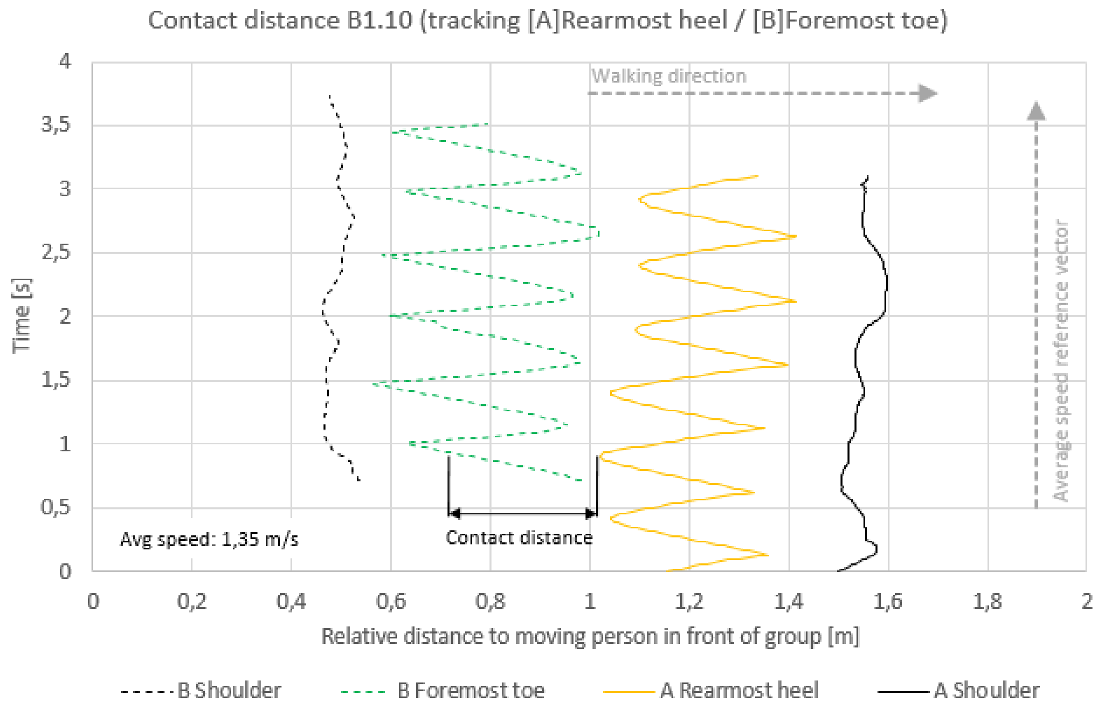

Figure C 32 - The contact distance for test B1.10 from the motion capture experiment, presented as a relative distance

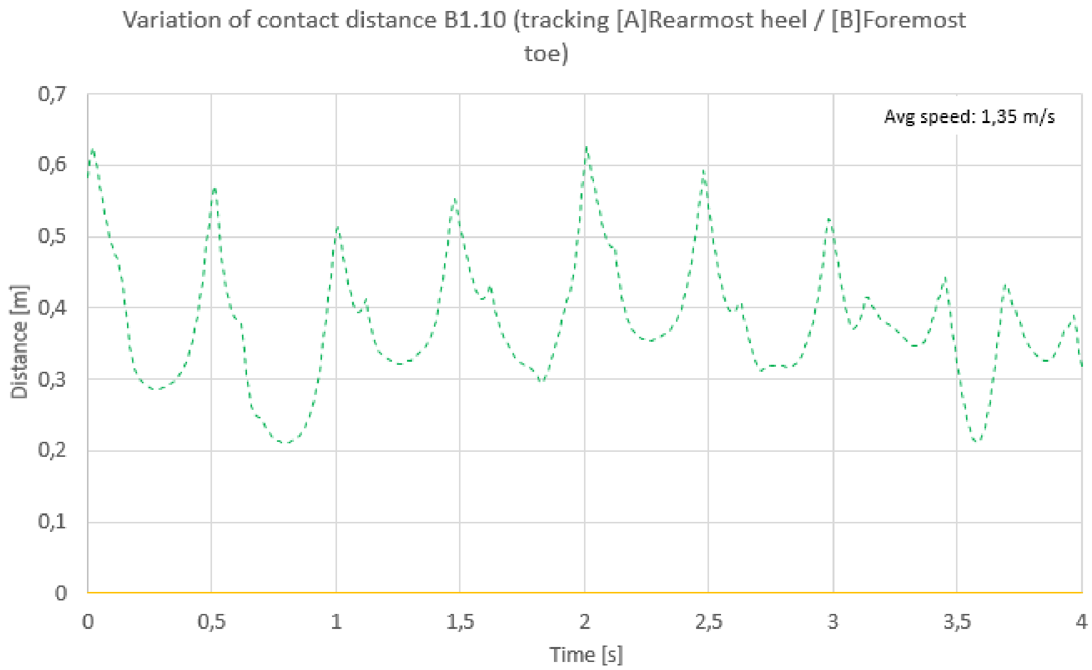

Figure C 33 - Variations of contact distance for test B1.10 from the motion capture experiment

Appendix D

Details regarding participants from the video capture experiment conducted in Lund, Sweden is presented in Table D 1.

Table D 1 – Details regarding the participants of the video capture experiment

Participant	Age [years]	Height [m]	Thigh length [m]	Shank length [m]	Ankle height [m]	Foot length [m]	Pref. speed [m/s]
1	24	1.67	0.40	0.39	0.08	0.26	1.14
2	17	1.77	0.41	0.38	0.10	0.30	1.04
3	19	1.89	0.46	0.42	0.07	0.31	1.41
4	20	1.73	0.43	0.39	0.09	0.26	1.35
5	19	1.62	0.42	0.36	0.12	0.24	1.15
6	20	1.98	0.52	0.42	0.10	0.33	1.37
7	20	1.85	0.43	0.42	0.10	0.30	1.08
8	20	1.96	0.47	0.43	0.13	0.29	1.52
9	19	1.73	0.41	0.34	0.12	0.27	1.18
10	18	1.60	0.41	0.36	0.11	0.26	1.28
11	20	1.66	0.44	0.38	0.09	0.27	1.30
12	22	1.75	0.46	0.36	0.12	0.27	3.04
13	20	1.69	0.44	0.36	0.08	0.26	1.25
14	26	1.88	0.44	0.41	0.10	0.33	1.22
15	20	1.87	0.47	0.41	0.09	0.31	1.18
16	19	1.82	0.48	0.38	0.09	0.28	1.18
17	19	1.80	0.44	0.40	0.11	0.29	1.06
18	21	1.80	0.42	0.39	0.10	0.29	1.43
19	18	1.83	0.40	0.47	0.11	0.31	1.33
20	19	1.67	0.40	0.40	0.09	0.27	1.32
21	18	1.80	0.45	0.40	0.10	0.29	1.25
22	19	1.85	0.45	0.40	0.09	0.29	1.27
23	20	1.94	0.47	0.45	0.10	0.31	1.32
24	21	1.76	0.43	0.42	0.08	0.26	1.12
25	27	1.94	0.42	0.42	0.10	0.31	1.16
26	20	1.88	0.50	0.39	0.10	0.29	1.32
27	19	1.83	0.42	0.42	0.10	0.30	1.30
28	21	1.86	0.48	0.41	0.10	0.31	1.15
29	19	1.88	0.50	0.42	0.10	0.31	1.49
30	20	1.85	0.45	0.41	0.09	0.29	1.19
31	18	1.95	0.50	0.47	0.10	0.32	1.49
32	19	1.69	0.47	0.38	0.09	0.25	1.49
33	22	1.81	0.43	0.42	0.10	0.30	1.37
34	20	1.77	0.51	0.38	0.10	0.28	1.25
35	20	1.72	0.51	0.35	0.09	0.26	1.56

Participant	Age [years]	Height [m]	Thigh length [m]	Shank length [m]	Ankle height [m]	Foot length [m]	Pref. speed [m/s]
36	19	1.81	0.50	0.37	0.10	0.29	1.24
37	21	1.81	0.50	0.37	0.11	0.29	1.28
38	19	1.71	0.44	0.41	0.09	0.27	1.41
39	19	1.81	0.53	0.39	0.11	0.28	1.03
40	19	1.79	0.46	0.38	0.10	0.29	1.10
41	20	1.71	0.46	0.39	0.08	0.29	0.93
42	26	1.83	0.43	0.42	0.11	0.29	1.30
43	20	1.81	0.43	0.44	0.09	0.28	1.30
44	21	1.91	0.46	0.44	0.11	0.32	1.16
45	19	1.88	0.45	0.44	0.11	0.31	1.30
46	20	1.99	0.53	0.45	0.10	0.31	1.23
47	21	2.02	0.52	0.49	0.10	0.33	1.20
48	19	1.72	0.47	0.37	0.10	0.30	1.18
49	19	1.63	0.40	0.36	0.12	0.26	1.16
50	20	1.64	0.42	0.36	0.13	0.24	1.15
51	20	1.80	0.46	0.41	0.11	0.30	1.14
52	20	1.87	0.49	0.40	0.09	0.29	1.29
53	19	1.86	0.54	0.40	0.10	0.29	1.25
54	25	1.61	0.44	0.34	0.08	0.25	1.13
55	24	1.92	0.46	0.47	0.11	0.31	1.22
56	19	1.90	0.47	0.43	0.11	0.29	1.23
57	22	1.74	0.51	0.40	0.10	0.26	1.28
58	22	1.65	0.47	0.37	0.10	0.25	0.93
59	24	1.72	0.44	0.41	0.09	0.27	1.28

Appendix E

Details of which unit and marker used at each participants during the motion capture experiment conducted in Dublin, Ireland can be found in Table E 1 and in Table E 2 details regarding participants is presented.

Table E 1 – Details regarding which Codamotion markers and Shimmer units were attached to each participant of the motion capture experiment

	Left foot		Right foot		Dist. between	Shoulder		Shimmer unit
Participant	**Back**	**Front**	**Back**	**Front**	**feet markers [m]**	**Lower**	**Upper**	**Lower back**
1	3	4	1	2	0.18	57	56	D8D9
2	9	10	7	8	0.17	12	11	DA70
3	15	16	13	14	0.17	18	17	D98B
4	21	22	19	20	0.16	24	23	DB49
5	15	16	13	14	0.17	18	17	D98B
6	21	22	19	20	0.16	24	23	D8D9
7	3	4	1	2	0.16	6	5	DB49
8	9	10	7	8	0.14	12	11	D870
9	15	16	13	14	0.17	18	17	D8D9
10	9	10	7	8	0.16	12	11	DB49
11	3	4	1	2	0.16	6	5	DA70
12	21	22	19	20	0.17	24	23	D98B
13	21	22	19	20	0.17	24	23	DB49
14	9	10	7	8	0.17	12	11	D98B
15	3	4	1	2	0.16	6	5	D8D9
16	15	16	13	14	0.16	18	17	DA70

Table E 2 - Details about the participants of the motion capture experiment

Participant	Sex [M/F]	Age [years]	Height [m]	Weight [kg]	Leg length [m]	Upper arm length [m]	Shoe length [m]	Hip width [m]	Shoulder width [m]	waist circumference [m]	pref. speed [m/s]	reaction time [ms]
1	F	25	1.64	58.4	0.760	0.305	0.280	0.215	0.310	0.595	1.60	1.60
2	M	35	1.83	85.4	0.820	0.350	0.320	0.240	0.390	0.900	1.70	1.80
3	M	25	1.77	87.8	0.830	0.350	0.320	0.230	0.370	0.860	1.70	1.80
4	F	40	1.65	58.0	0.800	0.340	0.275	0.240	0.270	0.700	1.50	1.30
5	M	31	1.75	91.2	0.810	0.345	0.320	0.270	0.360	0.970	1.40	1.80
6	M	24	1.74	71.4	0.830	0.330	0.300	0.220	0.350	0.860	1.80	1.90
7	M	27	1.78	78.3	0.840	0.335	0.300	0.260	0.380	0.860	1.50	1.60
8	F	30	1.67	60.2	0.840	0.330	0.280	0.240	0.300	0.670	1.60	2.10
9	F	27	1.62	100.6	0.860	0.320	0.235	0.230	0.340	1.030	1.70	1.60
10	F	28	1.72	59.1	0.850	0.356	0.295	0.245	0.300	0.720	1.50	1.50
11	F	25	1.64	70.9	0.870	0.325	0.290	0.240	0.340	0.850	1.20	1.80
12	F	33	1.74	62.8	0.850	0.330	0.300	0.260	0.320	0.730	1.50	1.60
13	M	29	1.84	81.2	0.830	0.330	0.320	0.270	0.340	0.940	1.60	1.70
14	M	48	1.79	91.9	0.870	0.360	0.330	0.270	0.340	0.860	1.50	1.90
15	F	42	1.72	52.8	0.830	0.320	0.200	0.240	0.290	0.670	1.10	2.00
16	F	35	1.73	69.0	0.890	0.330	0.300	0.270	0.300	0.820	1.60	1.70