A Novel Way of Measuring Inter-Person Distance: A Study Involving an Ultrasonic Measurement Device

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Abstract

The quantitative characteristics of people movement that form the fundamental diagram have an important role in the field of Fire Safety Engineering regarding evacuation. The fundamental diagram indicates the relation between crowd speed and crowd density (or inter-person distance) or flow of crowd and crowd density. These correlations are used in designing the means of egress in buildings and also computer simulations of evacuation. For either cases, the data of people movement is needed which is collected from evacuation experiments. Measuring these parameters is difficult when using traditional methods, e.g., video cameras. In this study, a new way of measuring inter-person distance by using an ultrasonic measurement device is investigated. The aim of this study is to verify the accuracy of inter-person distance data collected using an ultrasonic measurement device. As this measurement technique is a novel technology that is used for people movement, individual and group experiments were performed in order to obtain data. These controlled walking experiments were carried out in a corridor with a certain number of participants while one person carried the device. The accuracy of data obtained from the ultrasonic measurement device had been verified up to a specific inter-person distance, i.e., 2 m.

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A NOVEL WAY OF MEASURING INTER-PERSON DISTANCE:
A STUDY INVOLVING AN ULTRASONIC MEASUREMENT DEVICE

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DISCLAIMER

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Read and Approved

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Summary

The quantitative characteristics of people movement that form the fundamental diagram have an important role in the field of Fire Safety Engineering regarding evacuation. The fundamental diagram indicates the relation between crowd speed and crowd density (or inter-person distance) or flow of crowd and crowd density. These correlations are used in designing the means of egress in buildings and also computer simulations of evacuation. For either cases, the data of people movement is needed which is collected from evacuation experiments. Measuring these parameters is difficult when using traditional methods, e.g., video cameras. In this study, a new way of measuring inter-person distance by using an ultrasonic measurement device is investigated.

The aim of this study is to verify the accuracy of inter-person distance data collected using an ultrasonic measurement device. As this measurement technique is a novel technology that is used for people movement, individual and group experiments were performed in order to obtain data. These controlled walking experiments were carried out in a corridor with a certain number of participants while one person carried the device. The accuracy of data obtained from the ultrasonic measurement device had been verified up to a specific inter-person distance, i.e., 2 m. The results from individual and group experiments were mostly accurate with 5% of differences between actual inter-person distances and measured ones. Measurement, procedure and systematic errors that occurred while performing experiments can result in some measurement uncertainties.

Özet

Temel diyagramı oluşturan insan hareketlerinin nicel karekteristikleri, tahliyeye ilişkin yangın güvenliği mühendisliği alanında önemli bir role sahiptir. Bu temel diyagram, kalabalık hızları ve kalabalık yoğunluğu (veya kişiler arasındaki mesafe) veya kalabalık akışı ve kalabalık yoğunluğu arasındaki ilişkileri göstermektedir. Bu korelasyonlar binalardan kaçış yollarını dizayn ederken ve tahliyeye ilişkin bilgisayar programlarında kullanılır. Her iki durumda da, tahliye deneylerinden toplanan insan hareketlerine dair veriler gereklidir. Geleneksel yolları kullanarak mesela video kameraları, bu parametreleri ölçmek zordur. Bu tezde, ultrasonik ölçme cihazı kullanılarak yeni bir yolla kişiler arası mesafeyi ölçmek araştırılmıştır.

Bu tezin amacı, ultrasonic ölçme cihazı kullanılarak toplanan kişiler arası mesafeye ait verilerin doğruluğunu kanıtlamaktır. Bilindiği üzere bu ölçme tekniği yeni olduğundan, kişisel ve grup deneyleri veri elde etmek amacı ile gerçekleştirilmiştir. Bu kontrollü yürüyüş deneyleri bir koridorda belirli sayıda insan ile ve bir kişinin cihazı taşıması ile gerçekleştirilmiştir. Ultrasonik

ölçme cihazı ile toplanan verilerin doğruluğu belli bir mesafeye (2 m) kadar doğrulanmıştır. Deneylerden elde edilen sonuçlar %5 farkla kesindir. Deney sırasında oluşan bazı hataların varlığı bazı ölçüm belirsizliklarine yol açmıştır.

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1. Introduction

One of the research methods used in human behaviour in fire studies is experiments. In experiments, the researcher manipulates some characteristics of the situation and then measures to determine the effects of the manipulation that allows conclusions about cause and effect. Laboratory experiments are used to determine walking speeds and crowd densities of people during normal movement while specific measurements are taken under test conditions.

A central aspect of people movement in the area of Fire Safety Engineering is the fundamental diagram. The fundamental diagram describes the relationship between movement speed and density (or inter-person distance) in crowded situations. The correlation is used both in hand calculations and computer simulations. [2,10,12] However, one problem is that inter-person distance is difficult to measure accurately using traditional methods, e.g., video cameras, stopwatches and simple observation.

In recent years, the studies regarding people movement during evacuation have been influenced positively by the technological advancements, i.e., new data collection methods. The scientific data regarding the crowd movement has usually been collected in two ways in the past studies in order to determine the speed, density and flow rates of people by observing their movement in a specified place [1]. The first of these is 'timing' that the researcher used a timer between two certain points while walking within a crowd to evaluate the average speed of people. Meanwhile, other researcher observed the number of people passing through a predefined location (exit) during a particular period of time to estimate the flow rates of people. This way was implemented by Predtechenskii and Millinskii's [2] as well as Hankin and Wright's [3] studies. The other way, which has been used mostly in recent years, is analysing video footage in order to obtain the parameters needed for people movement during evacuation. There are also newest ways to track people trajectories. One of them is using Microsoft Kinect 3D-range sensors in order to obtain people trajectories [22].

After all, sufficient data of people movement in crowded conditions play a significant role. Thus, a new way to collect accurate data concerning the movement of crowds should be presented and integrated into design manuals and compulsory regulations.

A research was published by Thompson [1] which identifies '*the inter-person distance as the distance from the centre of the body of the 'assessing person' to the centre of the body of the 'obstructing person''*. The movement of a person is mainly affected by the position and distances between each other and obstacles. Thompson states that the most essential factor when assessing the crowd movement is the invasion of personal space-speed effect. While a person moves with the crowd, the speed of a person decreases regardless of body contact. The distance between people in a crowd is also important for the flow rate estimation. In other words, at low densities, there is no effect on walking speed. However, at high densities the inactivity as well as congestion will ultimately occur.

Thompson carried out several experiments by video recording of various groups as they left or entered a building. The experiments were performed in Edinburgh in 1994 and each building was chosen carefully to fulfil the objectives of the study. Thompson used video equipment and developed software in order to collect and analyse the new data regarding the movement of individual people. Then the new data was used to confirm the connection between inter-person distance and the walking speed. [1]

Other research was published in 2007 and studied fundamentals of pedestrian and evacuation dynamics [4]. The authors examined people's physical movement in the crowd and the behaviour of pedestrians as well. The main purpose of the study was to show the importance of the data regarding pedestrian dynamics that obtained from experimental studies on the computer modelling approaches. Frequently, Schadsschneider et al. stated that the validation and calibration of models becomes challenging with the deficiency of comprehensive experimental data. They claimed that well-controlled experiments would give more valid data. [4]

Another study was published in 2009 that compared the pedestrian fundamental diagram across cultures [5]. The authors stated that the connection between walking speed and density was not entirely understood. These parameters showed difference in specifications, text books and literature. Therefore, Chattaraj et al. studied if the reason of these alterations were caused by the cultural differences as well as change in the length of the corridor. The experiments were done separately in India and Germany in which subjects walked in normal conditions in the corridor, which was built up with chairs and ropes. The data was collected by video cameras and presented as fundamental diagrams respectively, i.e., Indian and German. The main outcome from this study is that the effect of cultural differences was confirmed and should be reflected in the fundamental diagram. [5]

The previous studies about the fundamental diagram show that the values are different in all. However, in all diagrams, there is an inverse proportion between speed and density. On the other hand, density has no impact on speed up to a certain point. Hence, many likely factors could affect the fundamental diagram. These differences probably because of the effects of measurement methods, experimental set-up, culture, collecting and analysing the data. In most of the experiments or observations video cameras are used in order to collect data. However, it is difficult to measure the parameters that form the fundamental diagram. In people movement experiments, the measurement methods that are applied for obtaining people speed, density and flow influence the fundamental diagram considerably. Thus, different measurement methods were used in many past studies and the way of performing experiments and analysing the results obtained by measurement methods are the main reasons of the discrepancies between several fundamental diagrams. In addition, applied measurements methods for the experiments are labour intensive, i.e., video cameras. A new way of measuring these parameters, e.g., inter-person distance, is a must to obtain accurate values in evacuation experiments.

1.1 Objectives

The aim of the study is to study an alternative way of measuring inter-person distance in evacuation experiments using ultrasonic measurement devices carried by people in the crowd. This type of system works according to the principle that ultrasonic sound is emitted from a speaker and the time until the sound bounces off an obstacle in front and reaches a microphone is measured. The time can then be used to calculate the distance to an obstacle (e.g. person) in front of the device (or person carrying the device). As it is a novel technology, it has not yet been properly calibrated and tested.

The main objective of present study is to demonstrate the accuracy of this newly introduced measurement technique, i.e., ultrasonic measurement device, to be used evacuation experiments.

1.2 Delimitations

As can be expected in all studies, some factors could restrict the research. Since this was an experimental study, the limited time affected the number of experiments which were carried out with participants at Lund University. Moreover, the availability of voluntary participants who were involved in the experiments was another restriction. Therefore, the number of participants was limited. The participants were restricted to adults and having similar body sizes, e.g., no children, since the ultrasonic measurement device carried on the chest area by a person. The experiments were limited to be arranged in corridors, i.e., the results are for only horizontal movement. In addition, the controlled experiments were performed and so the outcomes from this study do not reflect completely crowd movement during real evacuation processes.

2. Theory

In this section some theoretical knowledge regarding crowd movement are given.

2.1 Quantitative Elements

The total evacuation of a building in case of fire is an essential part for the design related to fire safety. Fire safety engineers must carefully estimate the time needed to evacuate the building in order to provide the occupants to reach a safe area. Therefore, calculating the evacuation time is one of the most important factors when considering the safety of people. In this section, a brief summary of current knowledge about various elements that affect the evacuation time quantitatively will be given. These elements form the fundamental diagram of pedestrian movement, as well.

2.1.1 Speed, Density and Flow

There are fundamental elements, which are used to describe people movement quantitatively. These fundamental elements are the speed, the density and the flow. These are also called in SFPE Handbook [6] as movement characteristics of the travel phase, which is a part of engineering timeline that represents the total evacuation process. The understanding of these elements is important in order to determine the characteristics of crowd movement during evacuation. There are also qualitative elements used in defining pedestrian dynamics but these are not in the scope of present study.

Speed $\boldsymbol{v}$ is the distance travelled by a moving person divided by time and the unit of speed mostly is m/s. Speed is a function of density, egress component, e.g., corridor, stair, etc., and mobility capability of occupants with regard to pedestrian movement [7]. Moreover, the factors that have an impact on speed regarding pedestrian movement are individual’s or group’s mobility, occupant density, lighting levels, presence of smoke, wall characteristic, floor surfaces, stair geometry, training and staff assistance [7].

Density $\boldsymbol{\rho}$ is the number of persons in a unit area of passageway [6] and its unit is generally persons/m^2. Some researchers presented density in their studies as the horizontal projected area occupied by the person over a unit area e.g., m^2/ m^2 [8].

The flow $\boldsymbol{J}$ is the number of persons passing a segment of the egress system per unit time (persons/s) [7]. One way of measuring flow of a pedestrian stream is to detect the time interval between two sequential pedestrians while passing the facility. Thus the flow can be expressed as $J = \Delta N / \Delta t$. N is the number of persons that passes the facility in that time interval. [9] The flow can also be determined by using fluid dynamics. The flow equation can be described as,

$$J = \rho\, v\, w$$

where, w is the width of the passageway, v is the walking speed along the passageway and ρ is the population density. This equation is known as fundamental traffic equation [6].

By dividing the flow by the width of passageway ($J_s = J / w$) introduces the specific flow. The specific flow $\boldsymbol{J_s}$ is the number of persons passing a segment of the egress system per unit time per unit of width of the egress segment (persons/s/m) [7]. This relation is referred as hydrodynamic relation [9].

2.1.2 Inter-Person Distance

Thompson [1] was the first using the term inter-person distance 'd'. He had described the inter-person distance as '*the distance from the centre of the body of the assessing person to the centre of the body of the obstructing person*'. The positions of people within the crowd and also the distances between them influence a person's movement as well as his walking speed. On the other hand, the relationship between speed and density is the basis of the fundamental diagram of pedestrian movement. However, population density measurement while observing movement of people is demanding. This situation leads to distinctive density descriptions that are found in the literature. For this reason, introducing 'inter-person distance' is an alternative way of defining pedestrian density.

Thompson converted circular spacing areas of individuals in a crowd into linear distances. Thus, he made a relationship between the inter-person distance, 'd', which is the distance between the person in front and the lateral distance between the side of the assessing person which is equal to '0.87d'. Then, the equation that is needed to calculate the area of a person in crowd was derived as below as well as the density. [1] Thompson's approach is illustrated in Figure 1.

As shown in Figure 1, the area of a person 'A' is calculated by multiplying the distance between the person in front 'd' with the lateral distance of '0.87d'.

$A = 0.87d^2$ (A: area per person, m^2) and (d: inter-person distance, m) [1]

The density can be obtained by taking the inverse of the area of a person.

$D = 1/A = 1/0.87d^2$ (D: crowd density, p/m^2) [1]

Moreover, these calculations are appropriate for horizontal and uni-directional movement of people in a crowd. By using these equations, collected data about crowd movement could be translated into average inter-person distance which also forms the fundamental diagram with walking speed of pedestrians other than density and flow of people.

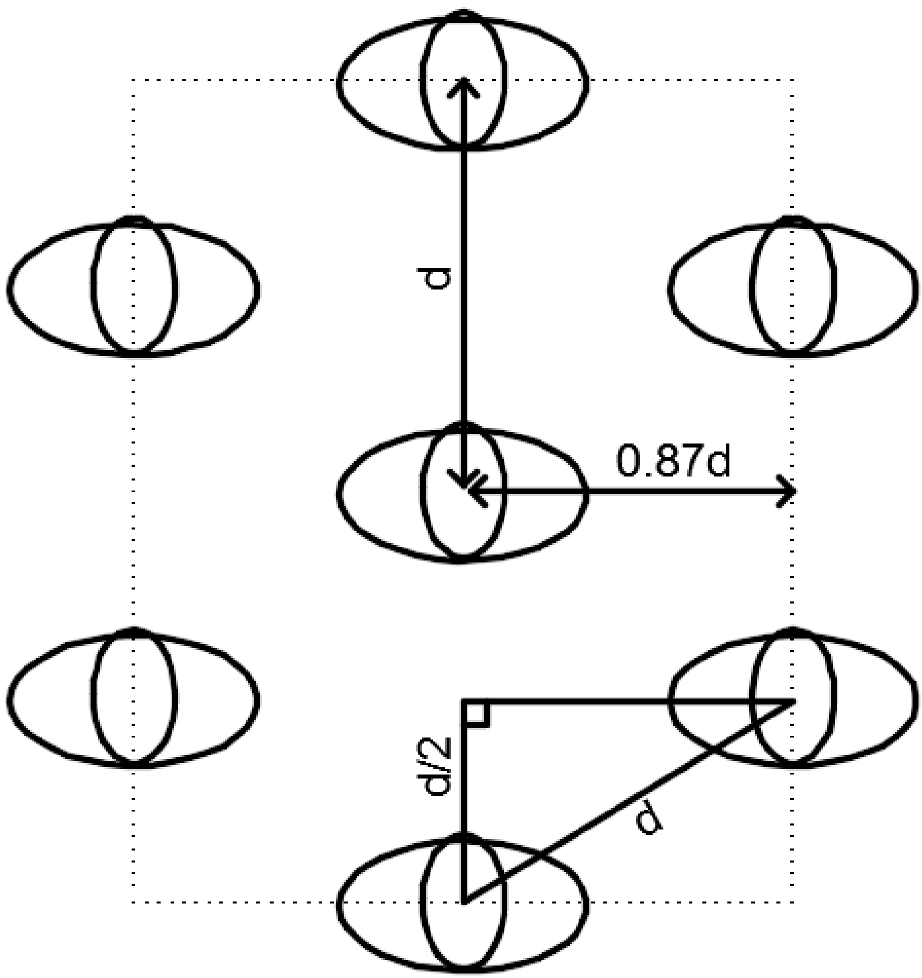

Figure 1. Inter-person Distance (d) introduced by Thompson [1] – re-drawn from original –

2.1.3 Fundamental Diagram

The fundamental diagram is a crucial subject when considering pedestrian movement in the area of Fire Safety with respect to planning the egress routes and exits in the buildings. In addition, the fundamental diagram shows a quantitative aspect for pedestrian dynamics used in engineering methods.

The relation between 'walking speed and crowd density (or inter-person distance)' or 'flow of people and crowd density' form the fundamental diagram of pedestrian movement. The interrelationships between these elements can be described at first that as the crowd density increases, the speed of the crowd will decrease accordingly speed of an individual will decrease. On the other hand, when the distance between people decreases (inter-person distance), that is related to density increase, the walking speed of people decreases. Thus, there is an inverse proportion between speed and density, however, a direct proportion between speed and inter-person distance. These relationships had been illustrated in many past studies [1,2,4,5,9,11,16].

Secondly, the relationship between flow and density is more complicated than between speed and density since flow is connected with the crowd speed and the crowd population. [8] Initially, when few people are present in a space, the densities are low accordingly flows will be low. As it gets crowded, densities will increase therefore flows will increase, in the meantime, crowd speed will decrease. This relation will change at some point that when the increase in density considerably high, people in a crowd slows down and eventually cannot move. When this situation happens, flows will begin to decrease. The increase in density results in a decrease in walking speed of people in a crowd. Because it gets too crowded for people to move, flow starts to decrease after a point as density still increases. [7]

An example of fundamental diagram illustrated in Figure 2, which shows the correlation between speed and density. In this figure, the movement speed and density's units are m/min and m^2/ m^2, respectively. This figure was obtained by Predtechenskii and Millinskii [2] in their studies about foot traffic flows in buildings. The different building components, i.e., passageways (horizontal movement), up and down stairs and openings (doors) were drawn. As can be seen from the figure, the shape of diagram differs for each component, however, the inverse proportion between speed and density is clearly noticeable. In addition, these values were collected when people were in normal movement, i.e., not in emergency conditions.

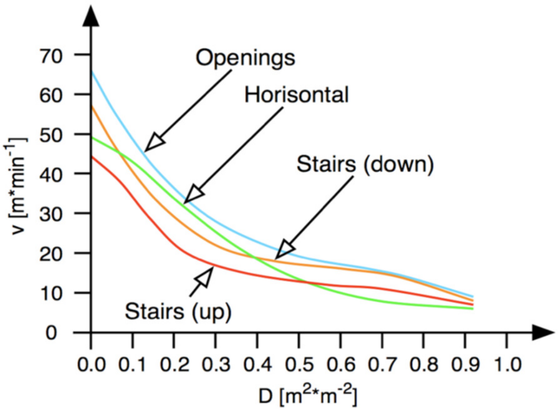

Figure 2. Fundamental Diagram - Movement speed as function of density for horizontal movement, stairs (up/down) and through openings (doors), drawn by Predtechenskii and Millinskii [2] – taken from [7] with permission

3. Literature Review

The publications and papers regarding inter-person distance, pedestrian dynamics, fundamental diagram, evacuation experiments are reviewed to gather information to guide this project.

3.1 Review of Past Studies

Fruin's [10] studies were not done particularly for evacuation, however, his observations on pedestrians had provided a broad insight on crowd movement analysis. The studies were conducted in train and bus stations and on streets by observing shoppers and commuters in order to obtain information about pedestrian movement in the crowd both quantitatively and qualitatively. Fruin investigated pedestrian movement along corridors, stairs, openings and also interested in conflict resolution and queuing. He introduced the term 'levels of service' based on crowd densities and defined their influence on flow rates. There are six levels of service standards described by Fruin from A to F where the population becomes dense for each level and at the end congestion occurs. He obtained data regarding pedestrian flow and presented them as graphs (fundamental diagram) where the flows and walking speeds are functions of 'pedestrian module' or in other words 'the inverse of crowd density' (m^2/person). He also interested in body dimensions of people and described 'body ellipse' dimensions (shoulder breadth and body depth) in order to determine the area of a human body on planar face. Table 1 shows the levels of service obtained by Fruin for walkways, stairs and queues.

Table 1. Fruin Densities / Levels of Service – taken from [7] with permission

Level of Service	Walkways (m^2/person)	Stairs (m^2/person)	Queues (m^2/person)
A	>= 3.3	>= 1.9	>= 1.2
B	2.3-3.3	1.4-1.9	0.9-1.2
C	1.4-2.3	0.9-1.4	0.7-0.9
D	0.9-1.4	0.7-0.9	0.3-0.7
E	0.5-0.9	0.4-0.7	0.2-0.3
F	<= 0.5	<= 0.4	<= 0.2

Predtechenskii and Millinskii [2] were Russian researchers who did studies about foot traffic flows in the 1960s and published a book titled 'Planning for foot traffic flow in buildings' which is based on occupant densities. The authors studied the people movement under normal and emergency conditions in public buildings, i.e., lots of different places including arenas and did approximately 3600 measurements. Their work is the basis for travel speed calculations in at least one evacuation model and frequently used in hand calculation methods. [7] Even though their studies were not especially for evacuation, their interest in the cases on horizontal passageways, stairs and openings contributed to understand movement characteristics of people in the field of fire safety and supplied movement data (speed, density and flow) in order to be used in designing egress components. They introduced a new way to quantify the density which is dimensionless (m^2/ m^2). Likewise, Fruin's body ellipse, they presented area of a person as the horizontal projection of human body on the building plan and called as 'area of horizontal projection of a person -f- '. The 'f' values were presented for the age (adult, youth and child) and types of dress (summer or winter clothes) as well as what they are carrying with them (a child or a luggage). The dimensionless density of flow was calculated as dividing the total area of people by the total area of floor occupied by flow. They also set an upper limit for dimensionless density as 0.92 m^2/ m^2. Moreover, an empirical expression for determining walking speed on a horizontal path was presented which depends on occupant densities. Furthermore, Predtechenskii and Millinskii investigated the flow behaviour at joints and merging points, as well.

Kendik [11] improved the correlations and methods related to pedestrian movement developed by Predtechenskii and Millinskii and applied them in evacuation process. Kendik compared the data from Predtechenskii and Millinskii's studies with the observations done in Germany regarding evacuation.

Togawa [12] was one of the first researchers who approached people movement as they behave like liquids, i.e., flow of people along a passageway, and developed equations based on fluid dynamics. Thus, his approach to pedestrian movement was the basis of hand calculation methods. [9] He observed commuters' movement along corridors, stairs and openings. Togawa estimated the time for evacuation of a building by presenting an equation that *'considers the flow time for an egress element, plus the time needed to traverse some distance in the egress system.'* [1,6]

Hankin and Wright [13] prepared a report for London Transport Board in order to collect data of pedestrian movement. They observed the passenger flow in London undergrounds and also carried out experiments with a group of students moving in a specified area. They then used the data that consists of walking speed, crowd density and crowd flow in order to obtain fundamental diagram of pedestrian movement. Data from London Transport Board is frequently used, but can provide overly optimistic estimates of egress time. [7] Some regulations still use these obtained movement characteristics data. [1]

Pauls's [14] observations were mostly on evacuation drills in tall office buildings. The researcher used stopwatches and video cameras while collecting data regarding people movement. Pauls mainly investigated the movement on stairs (down) and introduced the term 'effective width' which is the nett width used by people on stairs. Since there is a spacing between people and egress components (walls, railings, etc.) which allows clearance for body sway and balance.

3.2 Data Collection Methods

Some data collection and analysis methods found in the literature regarding pedestrian movement characteristics are presented below.

Helbing et al. [15] collected data with respect to people movement from a catastrophe happened during Hajj where the population in that area was too crowded. They used video recordings in order to obtain data for pedestrian movement and pedestrian dynamics, i.e., density, speeds, flows and stop-and-go, turbulent flows. They developed an algorithm to analyse the video recordings and obtain data to determine fundamental diagram, as well.

In another study called 'the fundamental diagram of pedestrian movement revisited' [16], several experiments were performed in a horizontal passageway and the data about pedestrian movement characteristics were collected by a new technique. This technique was used to record pedestrian flow characteristics automatically by using 'stereo video processing' which can monitor the trajectories of persons. As a result of this study by Seyfried et al., the pedestrian flow characteristics were obtained successfully but needs further development.

Hoogendoorn et al. [17] studied a way to determine pedestrian movement characteristics from various performed walking experiments. The data of individual movement was obtained from the observations that recorded by video cameras. By using series of video images and applying new methods, the individual's movement could be automatically detected and also tracking of pedestrians was accomplished. For data collection, some corrections on image processing were carried out, i.e., radiometric and lens distortion. Moreover, some methods were applied to improve the process of pedestrian tracking.

An interesting study [18] was published in Finland that presents a new technique for tracking people during evacuation experiments. Evacuation drills were performed in some offices, public buildings and the observations were made by using digital cameras and a newly used technique called Radio Frequency Identification (RFID). During evacuation drills, the participants were carrying RFID-tag (silicon chip) and at certain locations RFID- antennas were placed. People movement data was obtained by analysing both RFID results and video footages.

In another study [19], the walking experiments were performed under laboratory conditions and the pedestrian movement data was obtained by using laser scanner measurements and an algorithm respecting tracking of participants was carried out to transform the raw data into more useable data.

Lastly, in order to obtain inter-person distances in people movement experiments, some measurement techniques were applied in several previous studies, such as video recordings [1,20], radio frequency identification (RFID) [18], infrared sensors [21] and Microsoft Kinect 3D-range sensors [22]. All these measurement techniques should be implemented accurately to obtain valid data.

4. Experiments

Since ultrasonic measurement device had never been tested before in people movement studies regarding evacuation, individual experiments have been carried out in order to check whether the ultrasonic measurement device collects accurate data at first. These simple experiments have been done to ensure the accuracy of the data collected from ultrasonic measurement devices. The devices can then be used in comprehensive evacuation experiments in order to analyse people movement in the future. Afterwards, if the data is found to be needed for an improvement, the ultrasonic device was calibrated to get more reliable results. As it is a novel technology, one should expect uncertain and incorrect results.

Secondly, group experiments were performed after being ensured of the ultrasonic measurement devices provide accurate results from individual experiments. In the group experiments, uniformly distributed subjects moved together, i.e., normal movement, in a corridor while one person was carrying the ultrasonic measurement device. The accuracy of data was tested to investigate whether the measured result was from the person directly in front or the person in front at an angel or any obstacle inside the corridor. In addition, whether the body sway of nearby persons, i.e., arm swinging, could affect the measured data in dense conditions was also investigated. Meanwhile, the group experiments were recorded by video cameras. The purpose of group experiments was to determine the accuracy in more field-like settings.

4.1 Ultrasonic Measurement Device

The ultrasonic measurement device was designed and assembled as well as the software was developed by Dr. Daniel Nilsson in order to introduce a new way for measuring inter-person distance. The device comprises of two parts; the ultrasonic distance measurement part and the data logger part, connected to each other with a cable as well. A 9V battery was used to power-up the data logger. This type of system works according to the principle that ultrasonic sound is emitted from a speaker and the time until the sound bounces off an obstacle in front and reaches a microphone is measured. Both tools are considerably lightweight and look like small boxes. The ultrasonic distance measurement tool and data logger have the dimensions of 50 mm x 85 mm and 60 mm x 110 mm, respectively. The ultrasonic measurement device is shown in Figure 3, below.

Data are recorded every 1 second (s) by the data logger and the measured distances are shown in millimetres. The data is extracted by using computer software called 'Arduino'. Arduino [23] is an open-source electronics platform based on easy-to-use hardware and software. Arduino boards are able to read inputs and turn it into an output. Arduino Software is for writing codes and uploading them to the board.

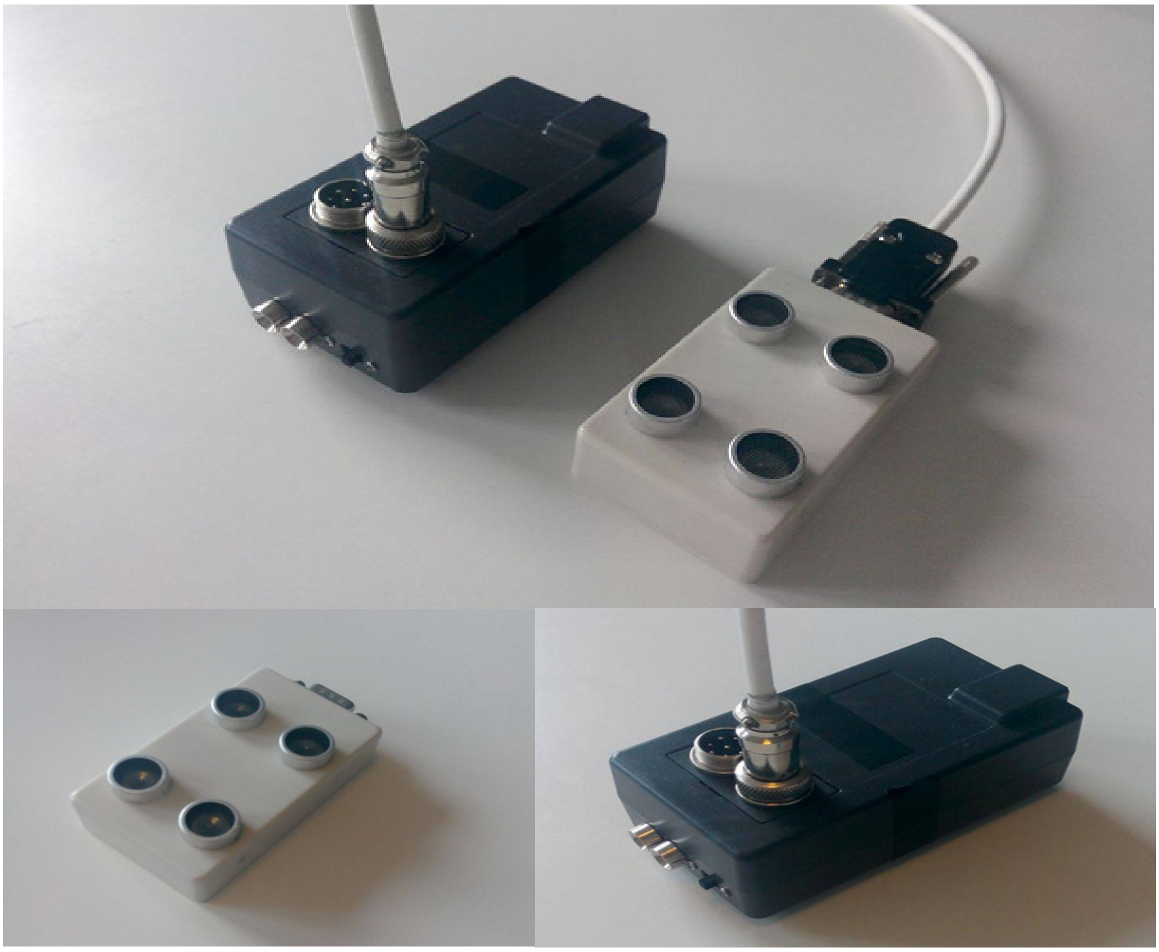

Figure 3. Ultrasonic Measurement Device - the ultrasonic distance measurement part (left) and the data logger part (right)

4.2 Participants

The participants who were involved in both individual and group experiments were International Master of Science in Fire Safety Engineering (IMFSE) students who were spending their 2nd and 4th semester at Lund University. The participants were from different countries (Turkey, Belgium, Canada, Russia, China, Malaysia, Palestine, Holland, Ecuador, Egypt, USA, Colombia, St. Lucia and Italy) all over the world. The number of subjects for group experiments were 15 and for last 2 individual experiments were 2. Their age range was from 23 to 31. The gender of participants was mixed but mostly consists of men (12 males and 3 females) as well as all of them were healthy and none of them had disability.

In addition, in this study, the experiments were based on only walking through a corridor and there was no significant risk that could give harm to participants physically or psychologically. As to consider the experiments involving human beings from ethical aspect, the subjects were all volunteered to participate in these experiments as well as they were well-informed before the experiments started.

4.3 Experimental Set-up

The methodology of individual and group experiments is described below.

4.3.1 Individual Experiments

In order to verify the accuracy of the data regarding inter-person distance that was collected by ultrasonic measurement device, initially, simple experiments with only two persons or one person and fixed obstacle (door) were performed. The distance between the person who is carrying the device and the obstacle (person or door) were measured and collected by ultrasonic device then the data was analysed. In these simple experiments, a laser distance measurer or measuring tape were used to justify the distance measured by the ultrasonic measurement device and also a string was used to attach two persons in order to keep the distance between persons to a fixed value in walking with people experiments.

The individual experiments were performed in two different corridors at the V-Building, Lund University, Sweden. One of them is named as 'narrow corridor' which is located on first floor. The length of the narrow corridor is 13 m and the width is 1.4 m along the corridor. Herewith, the effect of the side walls could be observed while running the experiments. The other corridor is wider as it were open place at basement floor. The length and width of the 'wider corridor' is 38 m and 3.2 m, respectively.

The individual experiments were performed in four main configurations. Firstly, in order to test up to which distances the ultrasonic measurement device can work, i.e., the device was designed to measure up to 4 m, namely **'standing'** experiments were performed. Secondly, namely **'walking towards door'** experiments were carried out to investigate the accuracy of data collected against a solid surface (door) while a person was walking towards door. Thirdly, namely **'walking-two persons'** experiments were performed in order to investigate the accuracy of data regarding the distance between two persons (inter-person distance) while walking together. Lastly, in order to study the effect of a solid object on to the reliability of results, the acrylic sheet was carried by the person in front at his back and for this reason namely **'walking-two persons-back'** experiments were performed. Furthermore, the ultrasonic measurement device was carried either on the clothes or acrylic sheet for each configuration, besides, 'walking-two persons-back' was carried only on the clothes. All experiments were carried out in narrow and wider corridors separately, except the last one was carried out only in wider corridor.

The ultrasonic measurement device's structure was explained in section 4.1. By taking into account the weight and the form of ultrasonic tool and data logger tool, it is easy to carry for a person. However, an important issue was that how the device can be fixed on to the person (chest area) who was carrying it. The ultrasonic tool must be carried properly, i.e., perpendicular to the floor. The data logger could fit into pocket of a jacket and the ultrasonic tool was carried by hand to be able to place it on the chest area of the person. When the ultrasonic tool was solely touching the clothes, it is referred as carried on the clothes while analysing the results. Another issue was that will the device give accurate data when the person wears normal clothes. While holding the device by hand, keeping it straight was important since the device should point at a correct obstacle with a right angle. In order to keep the ultrasonic tool straight, the device was taped on an acrylic sheet and then carried by hand with touching the chest area of the person. All tests were repeated either with carrying the device on the clothes or with carrying on the acrylic sheet.

Another issue was that while measuring the distances between two persons, the clothes of the predecessor, i.e., the person who is walking in front of the participant, might have a negative effect on the data collected by the device. The last part of the individual experiments was again performed between two persons but this time to see the effect of the clothes of the predecessor. Since clothes of predecessor could influence the unreliable results collected by the device. Therefore, the acrylic sheet was taped to the back part of the body of the person who is walking in front the participant, i.e., who is carrying the ultrasonic measurement device. The aim was to figure out the need of a solid object (acrylic sheet) in order to collect more accurate data.

Moreover, the ultrasonic measurement device can measure the distances up to 4m. Thus, the individual experiments were performed first for 0.5m then up to 4m with intervals of 0.5m. In other words, the data was collected for 0.5 m, 1 m, 1.5 m, 2 m ,2.5 m, 3 m, 3.5 m, 4 m and the results were shown in tables later in this study. Initially, each tested distances were adjusted by using laser distance measurer and for only walking with people experiments, a string was used to attach two persons with a length of measured distance. Thus, the distance between two persons was kept constant. Hence, the inter-person distance which was measured by ultrasonic measurement device could be checked through attaching two persons by using string with the given distance intervals.

The first individual experiment, i.e., **'standing'**, was performed just standing, the subject was not walking, i.e. no movement, in front of the door or the person. In other words, the data was recorded during the person was remained standing. The reason is that, if the device gives accurate results for actual measured distances.

The second individual experiment, i.e., **'walking towards door'**, was performed as the ultrasonic measurement device was carried by person while walking towards door in both narrow and wider corridors. The experiments were repeated 5 times in order to check if any unreliable data was collected.

The third individual experiment, i.e., **'walking-two persons'**, was carried out as the ultrasonic measurement device was carried by person while walking with another person directly front in both narrow and wider corridors by carrying the device either on clothes or on acrylic sheet. Two persons were attached each other with string for every measured distances in order to adjust the tested distances, so two persons could walk together at the same walking velocity. The subjects were one woman, one man and both adults. The experiments were repeated 5 times in order to check if any unreliable data was collected.

The last individual experiment, i.e., **'walking-two persons-back'**, was carried out as the acrylic sheet was placed to the back part of the predecessor's (the person who is walking in front of the participant) body. Since the acrylic sheet is a solid object, the results would be more accurate than the normal clothes. The ultrasonic device was carried by person while walking with another person in front who was carrying the acrylic sheet at his back. The device was carried on the clothes by participant. These experiments were performed only in wider corridor. The persons were adult woman and man and they were attached each other with string for the distances up to 2 m. The string was used to justify the actual tested distances and also they could walk in the same speed. The experiments were repeated 5 times in order to check if any unreliable data was collected.

All individual experiments were repeated 5 times. The reason is testing the equipment (ultrasonic measurement device) and the procedure which is applied to obtain data. As can be seen from the tables which are presented in appendices, the variation between each tests are below %5. In other words, there is not big differences between these tests, therefore, repeating the tests 5 times is a sufficient number.

Schematic drawings for individual experiments namely ‘walking-two persons’ and ‘walking-two persons-back’ are illustrated in Figure 4.

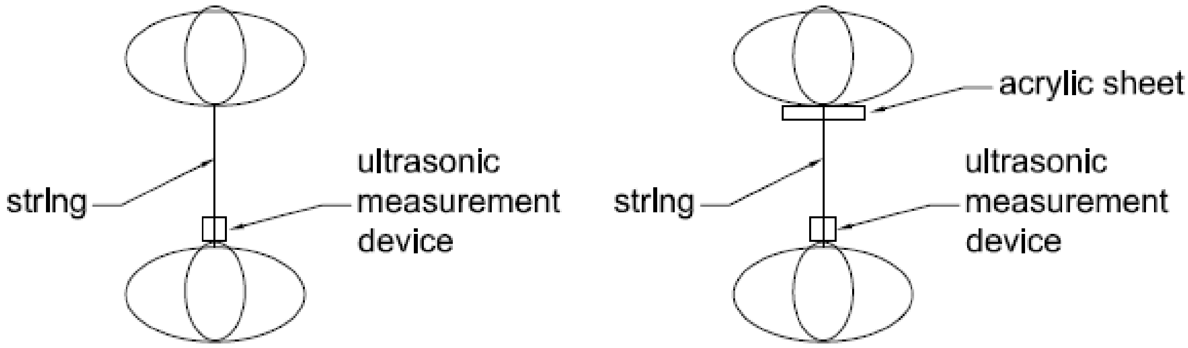

Figure 4. Schematic drawings for individual experiments, ‘walking-two persons’ (left) and ‘walking-two persons-back’ (right)

4.3.2 Group Experiments

After being ensured of the accuracy of the results that were obtained from individual experiments in order to measure the inter-person distances by using ultrasonic measurement device, the group experiments, i.e., controlled experiments, were performed. The observations and findings taken from individual experiments regarding how to obtain accurate and reliable data lead to determining the procedure of group experiments. The results are mentioned in section 5.

The group experiments were performed in a corridor on first floor of V-Building, Lund University, Sweden. The dimensions of the corridor are 38 m (length), 3 m (width) and 2.9 m (height). The sizes and utilization of corridor were convenient for positioning of the tools used during experiments i.e. video cameras as well as performing experiments with a group of persons. A schematic drawing of the corridor where the group experiments were performed and procedure of the group experiments are simple illustrated in Figure 5.

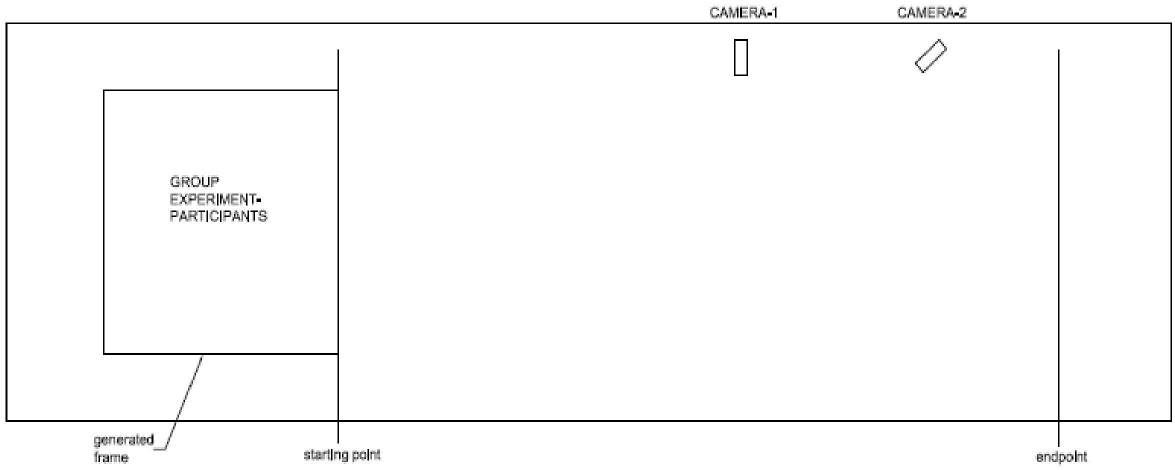

Figure 5. Schematic drawing of the corridor for group experiments

As an outcome from individual experiments which is mentioned in section 5, the ultrasonic measurement device could measure the distances between two persons up to 2 m reliably and certainly. Thus, the group experiments were carried out in four different cases. These were the inter-person distances for 0.5 m, 1 m, 1.5m and 2 m.

Another outcome from individual experiments which is mentioned in section 5 that the obtained data were more accurate when the person in front carries the acrylic sheet (solid object) at his back. Therefore, the person in front of the participant carried the acrylic sheet at his back while walking with the group of people. Meanwhile the ultrasonic measurement device collected data between the participant who carried the device and the person in front of her. Moreover, same as in individual experiments, two persons were attached each other with string for every measured distances in order to justify the tested distances.

The participants for the group experiments no.1 and no.2 were 15 persons. As the inter-person distances were increased, the number of participants were decreased in order to reduce the length of the generated frame. The participants walked together while only one person (the participant) carried the ultrasonic measurement device and the device collected data for the distance of the front person. The metronome with around 100 bpm (beats per minute) was used which is the normal walking pace of participants [24] to arrange the walking rhythm of the group, therefore, the participants walked with a harmony during the group experiments.

Two video cameras, which were Oregon Scientific ATC-2K, were used to record movie footage of the group experiments along corridor. The resolution of cameras was medium video format (320x240 pixels) and also the frame rate was 30 fps (frames per second). One camera was placed left side of the group’s movement with a height of 2.4 m as well as recording the experiments angularly. The other camera was located at the same height but this time pointing the corridor perpendicularly.

In order to obtain a uniform distribution of people during experiments for each measured inter-person distances, Thompson's [1] approach had been used regarding the relationship between inter-person distance and density. A detailed information has been given in section 2.1.2 about Thompson's studies concerning inter-person distance. Thompson converted inter-person distance (d) into the area needed for an individual (A) within the group of people. By using this relationship, one can calculate the area needed for an individual. In addition, by multiplying the individual's area with the number of persons that are present during the experiments, one can get the total area of the persons in where every individual have the same inter-person distance. Moreover, by taking the inverse of the individual's area, the density (persons/m^2) can be obtained. In these group experiments the densities were kept constant for each tested inter-person distances. The equations that were used to calculate the parameters, shown below. The set-up of the group experiments presented in Table.2.

$A = 0.87d^2$ (A: area per person, m^2) and (d: inter-person distance, m) [1]

$D = 1/A = 1/0.87d^2$ (D: crowd density, p/m^2) [1]

$\Sigma A = N \times A$ (N: number of persons)

By using the needed area of the persons, a 'frame' had been created for each inter-person distance. Hence, every participant fit in this frame and walked together for a specified distance. The specified distance was 10 m which was assumed to be enough to collect intended data. The frame was generated by using a rope which surrounded the persons. While running the group experiments, it had been told to participants not to break the frame generated with the help of a rope, and also walk together carefully. The width of the frame was fixed to 2 m and the length of the frame changed according to the needed total area of persons in order to provide the required inter-person distance.

Table 2. Group Experiment Parameters

Group Experiment No	**Inter-person Distance (d)**	**Number of Persons (N)**	**Area per Person (A)**	**Crowd Density (D)**	**Total Area of Persons (ΣA)**	**Generated Frame (w x l)**
-	**m**	**-**	**m^2**	**persons/m^2**	**m^2**	**m**
1	0.5	15	0.22	4.55	3.3	2 x 1.7
2	1	15	0.87	1.15	13	2 x 6.5
3	1.5	8	1.96	0.51	15.7	2 x 7.9
4	2	6	3.48	0.29	20.9	2 x 10.5

As can be seen from Table 2, the number of persons had been reduced to 8 persons and 6 persons for the inter-person distances 1.5 m and 2 m, respectively. The reason was that if the number of persons were kept 15, the length of the group was too long that it could not fit in the corridor when the group walked 10 m. However, this change did not affect the aim of the experiments. Since the main goal in the group experiments was to observe the effect of other persons at right and left side of the person who was carrying the device.

Every set of group experiments were repeated 3 times in order to avoid the errors that could happen while running the experiments. For d: 1.5 m and d: 2 m, there are slight differences between tests. Even though there are significant differences between tests for each measured distances (d: 0.5 m and d: 1 m), repeating tests 3 times is sufficient to show the variation.

The snapshots of each group experiments are presented below. Figure 6 is for the inter-person distance d: 0.5 m with 15 subjects and Figure 7 is for d: 1 m with 15 subjects. Figure 8 and Figure 9 show the distances d: 1.5 m and d: 2 m with 8 subjects and 6 subjects, respectively.

Figure 6. Snapshots for d: 0.5 m , N: 15 persons – Group Experiment No.1

Figure 7. Snapshots for d: 1 m , N: 15 persons – Group Experiment No.2

Figure 8. Snapshots for d: 1.5 m , N: 8 persons – Group Experiment No.3

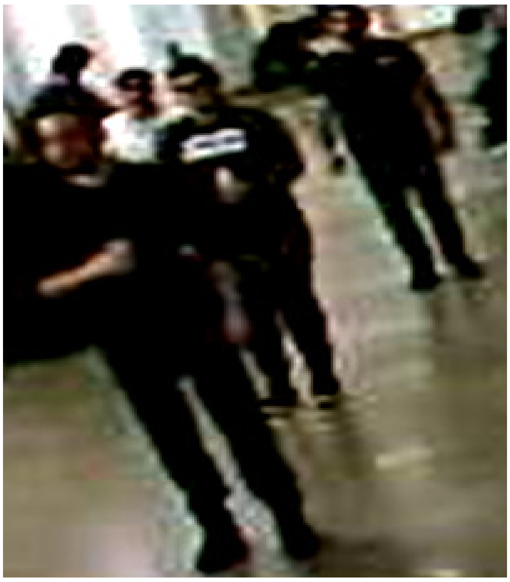

Figure 9. Snapshot for d: 2 m , N: 6 persons – Group Experiment No.4

5. Results

The results of individual and group experiments are presented in this section separately. The most accurate data regarding inter-person distances are shown in tables whereas the raw data of some experiments are presented in appendices.

5.1 Individual Experiments

The individual experiments were performed in four main configurations, these are, 'standing', 'walking towards door', 'walking-two persons' and 'walking-two persons-back'. The methodology of these experiments were explained in experimental set-up section.

5.1.1 'Standing'

Each experiment took approximately 15 seconds. The average distance that is taken for each time step and the number of '0' or unreliable values that the data logger recorded over each time step, is shown in tables below. The percentages of differences between actual distances and measured distances are presented, as well. Moreover, negative sign (-) means the measured distance is lower than the actual distance, on the contrary, positive sign (+) means higher values. Table 3 shows the results for the experiments between a person and an obstacle (door). The average distances, that are measured by ultrasonic measurement device, are slightly lower than the actual distances mostly. Throughout the time steps, the measured distances fluctuate too close to the actual distances; i.e. lower or more. As shown in table 3, the percentages of differences are quite low, that the biggest difference is -4.3% which can be acceptable. However, for 3.5 m and 4 m, the device measures unreliable data. Hence, the device can be used for the distances up to 3 m. As can be seen from the table, the effect of carrying the device either on clothes or on acrylic sheet does not have importance on the results. The corridor width does not affect the results significantly, as well. In addition, the side walls do not affect the data collected by ultrasonic device, but one can argue that this can lead to the unreliable data for 3.5 m and 4 m.

Table 3. Between a Person and a Door

		NARROW CORRIDOR								WIDER CORRIDOR							
	Distance (mm)	500	1000	1500	2000	2500	3000	3500	4000	500	1000	1500	2000	2500	3000	3500	4000
On Clothes	# of '0' or unreliable values over 16 steps	none	none	none	none	1	2	all	all	none	none	none	none	none	none	all	all
	Average Distance (mm)	508	992	1485	1989	2457	2958	0	0	486	988	1478	1963	2473	2964	0	0
	% of differences	1.6	-0.8	-1.0	-0.6	-1.7	-1.4	-	-	-2.8	-1.2	-1.5	-1.9	-1.1	-1.2	-	-
On Acrylic Sheet	# of '0' or unreliable values over 16 steps	none	none	none	none	1	none	all	all	none	none	none	none	none	none	all	all
	Average Distance (mm)	500	987	1471	1962	2443	2947	0	0	494	957	1468	1970	2443	2942	0	0
	% of differences	0	-1.3	-1.9	-1.9	-2.3	-1.8	-	-	-1.2	-4.3	-2.1	-1.5	-2.3	-1.9	-	-

The results for the experiments of between two persons can be seen in Table 4. Likewise, the results in Table 3, the measured distances fluctuate close to the actual ones, however, for the distance 2.5 m that measured in narrow corridor by carrying on acrylic sheet shows a little higher results where the difference is 5.5%. For other measured distances in narrow corridor, the percentages of differences are lower than 2.9. The results are trustworthy up to 3 m in narrow corridor, besides, for 2.5 m and 3 m, the number of incorrect data considerably higher. On the other hand, the device can measure up to 2 m for the experiments in wider corridor. This can be explained as the device cannot detect the body dimension (breadth) of the front person after 2 m because of the other obstacles just front e.g. door, wall, etc. Perhaps the device tries to measure other obstacles, for this reason gives inaccurate results. In wider corridor, the percentages of differences vary from 0.3 to 4.4, except for actual distance 0.5m where the difference is 8.6%. Moreover, the way of carrying the device does not influence the results substantially.

Table 4. Between Two Persons

		NARROW CORRIDOR								WIDER CORRIDOR							
	Distance (mm)	500	1000	1500	2000	2500	3000	3500	4000	500	1000	1500	2000	2500	3000	3500	4000
On Clothes	# of '0' or unreliable values over 16 steps	none	none	none	none	8	11	all	all	none	none	none	none	all	all	all	all
	Average Distance (mm)	492	1016	1511	2011	2488	3037	0	0	522	1036	1533	2006	0	0	0	0
	% of differences	-1.6	1.6	-0.7	0.5	-0.5	1.2	-	-	4.4	3.6	2.2	0.3	-	-	-	-
On Acrylic Sheet	# of '0' or unreliable values over 16 steps	none	none	none	none	6	7	all	all	none	none	none	none	all	all	all	all
	Average Distance (mm)	498	1000	1544	2021	2638	3012	0	0	543	1013	1515	1995	0	0	0	0
	% of differences	-0.4	0	2.9	1.1	5.5	0.4	-	-	8.6	1.3	1.0	-0.3	-	-	-	-

5.1.2 'Walking Towards Door'

The subject (woman, adult) was in normal movement and walked from 4 m to 0.5 m against door which took nearly 5 seconds. So, the walking speed was 0.7 m/s. The Table 5 shows the results for walking towards door by carrying the device on clothes or on acrylic sheet in narrow or wider corridors. Even though the experiments were repeated 5 times, the best results are shown in the table below. In all cases, the device gives accurate values up to 3 m, i.e. the distances higher than 3 m cannot be measured by ultrasonic measurement device. In narrow corridor, the percentages of differences vary from 1.6 to 17.8 when the device carried on clothes. For the actual distance 1 m the percentage is high, e.g., 17.8%, however most of them are below 10%. In wider corridor, the number of high percentages of differences are more, e.g., 37%, 31.5%. The width of the corridor does not affect the results as well as how the device was carried by person.

Table 5. The results for walking towards door from 4 m to 0.5 m

	NARROW CORRIDOR				WIDER CORRIDOR			
	Time (s)	Actual Distance (mm)	Measured Distance (mm)	% of differences	Time (s)	Actual Distance (mm)	Measured Distance (mm)	% of differences
On Clothes	0	4000	0	-	0	4000	0	-
	1	3500	0	-	1	3500	0	-
	2	3000	2953	-1.6	2	3000	3097	3.2
	3	2000	2170	8.5	3	2000	2272	13.6
	4	1500	1432	-4.5	4	1500	1380	-8.0
	5	1000	822	-17.8	5	1000	685	-31.5
	6	500	541	8.2	6	500	468	-6.4
On Acrylic Sheet	0	4000	0	-	0	4000	0	-
	1	3500	0	-	1	3500	0	-
	2	3000	3042	1.4	2	3000	2882	-3.9
	3	2500	2391	-4.4	3	2000	2059	2.9
	4	1500	1669	11.3	4	1500	1252	-16.5
	5	1000	1037	3.7	5	1000	630	-37.0
	6	500	592	18.4	6	500	541	8.2

5.1.3 'Walking-Two Persons'

In narrow corridor, the walking distance was 8 m and each experiment took approximately 10 seconds, thus, the walking speed was 0.8 m/s. In wider corridor, the walking distance was 10 m and each experiment took approximately 12 seconds, thus, the walking speed was 0.83 m/s. The results are shown in the Table 6. The most accurate values are presented even though the experiments were repeated 5 times. Furthermore, the average distances and the number of '0' or unreliable values are presented in the table. The percentages of differences between actual distances and measured distances are presented, as well.

As can be seen from the table, the ultrasonic measurement device collects accurate data for the distances up to 1.5 m for all cases with below 5.5% differences. However, for the distance 0.5 m in wider corridor the difference is 9.6%. In some cases, the device could measure 2 m but the number of unreliable data are significantly high and with a difference of 6.4%, therefore, it is meaningful to conclude as the device could not measure the distances higher than 1.5 m. Moreover, the measured distances fluctuate close to the actual distances. Likewise, in other individual experiments, the width of the corridor and the way the device carried do not influence the results remarkably.

Table 6. The results for two persons walking together

		NARROW CORRIDOR								WIDER CORRIDOR							
	Distance (mm)	500	1000	1500	2000	2500	3000	3500	4000	500	1000	1500	2000	2500	3000	3500	4000
On Clothes	# of '0' or unreliable values over 11 steps	2	none	7	all	all	all	all	all	5	none	5	7	all	all	all	all
	Average Distance (mm)	477	945	1494	0	0	0	0	0	476	966	1459	1872	0	0	0	0
	% of differences	-4.6	-5.5	-0.4	-	-	-	-	-	-4.8	-3.4	-2.7	-6.4	-	-	-	-
On Acrylic Sheet	# of '0' or unreliable values over 11 steps	none	none	5	9	all	all	all	all	5	2	3	all	all	all	all	all
	Average Distance (mm)	521	1003	1431	1984	0	0	0	0	548	1006	1469	0	0	0	0	0
	% of differences	4.2	0.3	-4.6	-0.8	-	-	-	-	9.6	0.6	-2.1	-	-	-	-	-

5.1.4 'Walking-Two Persons-Back'

The last individual experiments were performed in order to check if the ultrasonic measurement device could measure the distance '2 m' when the person in front carries a solid object at his back. 2 m cannot be measured within the previous experiments (walking-two persons). And also, whether the device could collect the data without errors or unreliable values for the distances up to 2 m. As can be seen from the Table 6, the device cannot give accurate values after 1.5 m when the person in front wears normal clothes. The walking distance was 10 m, each experiment took approximately 12 seconds, thus, the walking speed was 0.83 m/s. Table 7 shows the most accurate average distances and the number of '0' or unreliable values. The percentages of differences between actual distances and measured distances are presented, as well.

As can be seen from the Table 7, the ultrasonic measurement device gives reliable data for each distances. The measured distances fluctuate very close to the actual distances. The percentages of differences for 0.5m is -1.2%, for 1 m is -3.5%, for 1.5 m is -3.2% and lastly for 2 m is -1.2%. These percentages are quite low and acceptable. When compared to the results of the predecessor wearing normal clothes (Table 6), the values are more reliable and the number of errors are less, especially for the distance 2 m.

Table 7. The results for two persons walking together with the predecessor carrying sheet at back

Distance (mm)	500	1000	1500	2000
# of '0' or unreliable values over 11 steps	none	none	none	3
Average Distance (mm)	494	965	1452	1975
% of differences	-1.2	-3.5	-3.2	-1.2

As an important outcome from the performed individual experiments, the software that was written for ultrasonic measurement device do not need any calibration since the data is reliable and accurate up to some specified distances. Therefore, the group experiments were performed without calibration of the software.

5.2 Group Experiments

The outcomes from group experiments are presented in this section. The accuracy of the ultrasonic measurement device is mainly the focal point while analysing the results.

The times, walked distances and calculated walking speeds are shown in Table 8 for each measured distances by ultrasonic measurement device. For all cases, walked distance is the same, namely 10 m. The approximate times and walking speeds of the group are presented. For d: 0.5 m case, the time is the longest one as expected since the crowd was too dense to walk together. Therefore, the walking speed is very low compared to other cases. As the distances between people in the group increases, persons can walk freely, i.e., not affected by other bodies and the walking speeds reach a normal value. [7] The walking speeds 1.0 m/s and 1.25 m/s for the inter-person distances 1 m, 1.5 m and 2 m are normal individual speeds. When the crowd becomes denser, walking speeds of individuals decrease significantly as can be seen from d: 0.5 m. This situation can be considered as stagnation has been occurred because of the high densities (persons/m^2). This circumstance is the bases of fundamental diagram of people movement.

Table 8. Times, Walked Distance and Walking Speeds for each Group Experiment Cases

Group Experiment No.	Inter-person Distance (d)	Time	Walked Distance	Walking Speed
-	**m**	**s**	**m**	**m/s**
1	0.5	25	10	0.4
2	1	10	10	1
3	1.5	8	10	1.25
4	2	8	10	1.25

Table 9 shows the obtained data from group experiments that were performed for measuring the inter-person distances. The group experiments were performed for 4 cases by changing the inter-person distances in every case, i.e. 0.5 m, 1 m, 1.5 m and 2 m. Each group experiment was repeated 3 times, so it is shown as a separate column called 'exp. no.' in the table. The number of '0' or unreliable values are presented for each experiment. The average distances are taken over time steps for each experiment, as well. The most accurate values, i.e., the closest value to the actual distances with less unreliable values, are marked in grey for every group experiments. The percentages of differences between actual distances and measured distances are also presented.

For the inter-person distance 2 m, the raw data fluctuates very close to actual distance with -2.2% difference. The obtained average distance, 1957 mm, is very close to the actual distance 2 m. Moreover, the unreliable data is gotten 2 times over 8 time steps. Similarly, for d: 1.5 m, the average distance is close to actual one with 1419 mm and the percentage of difference is 5.4. However, in this case the data is all reliable, i.e., no errors in measured distances by the device.

The collected data for the inter-person distance 1 m is accurate but a little lower than the actual one, i.e., 898 mm or -10.2% difference. Moreover, for d: 0.5 m, the results are again lower than the desired value. The percentages of differences are significantly high, e.g., -44.2%, -26.8% and -23.0%. The best result is with -23.0% difference that the average distance is 385 mm where the intended value is 0.5 m. For both cases, the number of '0' or unreliable values are zero.

Table 9. The Results of Group Experiments

Group Experiment No.	Inter-person Distance (mm)	Exp. No.	# of '0' or unreliable values	Average Distance (mm)	% of differences
1	**d=500 mm**	1	none	279	-44.2
		2	none	366	-26.8
		3	none	385	-23.0
2	**d=1000 mm**	1	none	898	-10.2
		2	none	779	-22.1
		3	none	778	-22.2
3	**d=1500 mm**	1	none	1416	-5.6
		2	none	1330	-11.3
		3	none	1419	-5.4
4	**d=2000 mm**	1	2 (over 8 steps)	1947	-2.7
		2	2 (over 8 steps)	1885	-5.8
		3	2 (over 8 steps)	1957	-2.2

6. Discussion

In this section, the inferences from individual and group experiments are analysed. The main concern is the accuracy of this new measurement technique introduced throughout the present study regarding measuring inter-person distances. The reason is that ultrasonic measurement device is a new tool which is planned to be used in human related experiments concerning pedestrian movement in fire safety related areas. By performing simple experiments presented in this study, the ultrasonic measurement device could be accepted as applicable in the researches regarding people movement. More comprehensive experiments respecting measuring inter-person distance can be performed by using ultrasonic measurement device instead of traditional tools, i.e., video cameras.

Firstly, the outcomes from individual experiments are discussed. The results are accurate for the distances up to 3 m for most of the individual experiments. However, the ultrasonic measurement device cannot measure the distances 3.5 m and 4 m absolutely. One must bear in mind that there could be some inconvenient circumstances during the experiments which could lead to some errors or unreliable values in results. These could be human related errors, i.e., not carrying the device properly, not setting the actual distances correctly at the beginning of the experiments or the string between persons cannot be kept stretched during walking experiments. Moreover, the ultrasonic measurement device could give errors while running the experiments regarding its hardware. These errors are measurement errors that are related to the equipment.

As to discuss the accuracy of the ultrasonic measurement device, first and second individual experiments namely, ‘standing’ and ‘walking towards door’, were performed in order to test how the equipment collects accurate data. In ‘standing’ experiments, the device obtains accurate data up to 3 m and the percentages of differences between actual and measured distances are mostly below 5%. However, in ‘walking towards door’ experiments, the percentages of differences deviate in a wide range. On the contrary, third and fourth individual experiments namely, ‘walking-two persons’ and ‘walking-two persons-back’, were performed in order to test the procedure that is employed. The percentages of differences are usually below 5% for either individual experiments. As to estimate measurement uncertainty, it is acceptable to conclude as 5% for both equipment and procedure uncertainties.

Another outcome from the individual experiments is that, the way of carrying the device either on clothes merely or on the acrylic sheet do not affect the data collected as far as the device was held straight and parallel to the body. The carrier should be made sure of holding the device properly while walking particularly.

Throughout the walking experiments with two persons, the ultrasonic measurement device always measured the distances directly the body front. In other words, the device did not count the arm or leg swinging of the person in front, it seemed to measure the distance to the centre of the body. On the contrary, the fluctuations around the measured distance could be affected by the arm or leg swinging of the person in front. Or, the reason behind this issue is that the actual distance cannot be justified correctly by using string to attach people. These errors are procedural errors. As can be seen from Figure 5 and 6, the string between two persons is not stretched all the time throughout the experiments. This shows that even though the actual distance was justified at the beginning, during walking with the group the string could not been kept stretched. Therefore, the results were lower than the expected distances.

In first two individual experiments, errors that were encountered were related to the device. For example, obtained data are lower or higher than the desired one. However, differences were below 5% which can be acceptable. In last two individual experiments, errors were related to procedure that was employed, i.e., string was not kept stretched between two persons, the device were not carried properly. However, the differences were again below 5%.

In addition, the results are similar in narrow and wider corridor, however in wider corridor the ultrasonic measurement device could detect other obstacles when the distances between two persons more than 2 m.

Another point in walking experiments with two persons is that the ultrasonic measurement device gives more accurate data when persons in front carries an acrylic sheet at his back part of his body where the device pointing at. In other words, the device is more suitable to be used through solid surfaces, so it can detect more accurately and also the clothes can affect the results negatively. Since clothes are more flexible compared to sheet, while person is walking, the clothes also moves but irregularly which can be the reason of incorrect data. Moreover, the sound bounced off hard surfaces better.

Secondly, the group experiments' results are analysed. As per the outcomes from individual experiments, group experiments' methods were determined. The primary purpose of group experiments is to figure out how the ultrasonic measurement device works when there are more people present and also the accuracy of data obtained under this situation.

The results were presented in Table 9. The most important case is the group experiment no.1 in where the inter-person distance is 0.5 m and the higher percentages of differences were obtained, e.g., -23%. As participants were walking very close to each other as well as invading each other's personal spaces, the ultrasonic measurement device's main principle could be obstructed which is measuring the distance from the person directly in front. Since the results are showing lower values than the actual inter-person distance, one can suspect that the reason behind this condition is the effect of other bodies in front of the participant. The intended value is the distance from the person in front, however, the other persons' arms and half of their bodies could invade the area between these two persons. From the participant's perspective, the reason of low values is not the other persons' invasion of the area between participant and predecessor. Because during the experiments she observed that there was not significant invasion to the device which could influence the results negatively. On the other hand, the actual distance probably could not be protected, i.e., while walking with group of people (walking distance was 10 m), even though the inter-person distance was 0.5 m at the beginning. Due to the fact that, the persons were too dense as well as walked together hardly. In other words, the distances between persons had changed in progress of time.

For the other 3 cases, i.e., inter-person distances 1 m, 1.5 m and 2 m, the results are as expected since there is no invasion of the individual's areas in where the ultrasonic measurement device pointing at. However, for the distance 1 m, the results are a little lower with 10% of difference, perhaps the distance could not be arranged properly. For the distances 1.5 m and 2 m, the percentages of differences are -5.4% and -2.2%, respectively. Moreover, at some time steps the values are inaccurate for the inter-person distance 2 m. For the other cases, the ultrasonic measurement device collects data without giving an error.

The reason behind relatively low values were obtained in group experiments no.1 (d: 0.5 m) and no.2 (d: 1 m) is that procedural errors were occurred. For example, string was not kept stretched during walking with group of people. There are also systematic errors that could cause lower obtained data from group experiments which are shown in Table 9. For example, other participants arm swinging could block the ultrasonic measurement device, so the device cannot detect the distance from the person in front which is the aim of this study. The body sway of the participant who is carrying the device could also have an effect on the lower results.

Finally, controlled group experiments were performed for laminar flow of people where participants were uniformly distributed and walked straight ahead. In individual experiments, participants moved in pairs. If these experiments were performed in a more turbulent flow situation, the ultrasonic measurement device could not fulfil its purpose since the other people's bodies and arms would invade the area between the participant who is carrying the device and the participant in front.

7. Conclusions

In this study, a new measurement technique called 'ultrasonic measurement device' had been introduced concerning inter-person distances in order to be used in pedestrian movement experiments in the field of evacuation. The essential outcomes from individual and group experiments are mentioned in this section. The study primarily shows that the ultrasonic measurement device gives accurate values when used for the distances up to 2 m in people movement experiments. In addition, the ultrasonic measurement device collects more reliable data while pointing at a solid surface since the sound bounced off hard surfaces better. The study also indicates that the data obtained from ultrasonic measurement device is from the obstacle directly in front. Moreover, the movement of the limbs of the person in front do not affect the results. Furthermore, the ultrasonic measurement device must be carried carefully during walking experiments in order to get accurate values.

Moreover, the advantages of this newly measurement technique are that the ultrasonic measurement device is relatively cheap, the device is easy to be assembled and the device is practical to be used in pedestrian movement experiments. However, the procedure of experiments must be carefully applied.

The accuracy of data obtained by ultrasonic measurement device regarding inter-person distances had been verified which is the purpose of this present study.

Future Work

For future studies, the ultrasonic measurement device and the software need calibration in order to measure the inter-person distances more than 2 m in crowd movement experiments. More extensive walking experiments can be performed with large number of people and more people carry ultrasonic measurement devices. Since in this study the experiments were only performed in a corridor, future experiments can also be carried out through exits or on stairs, however care must be taken. If more comprehensive experiments are performed, more data will be collected regarding inter-person distances so a new fundamental diagram of pedestrian movement can be obtained.

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9. Appendices

Appendix A – Individual Experiments

Table A 1. Raw Data of 'Walking-Two Persons' with Clothes at Narrow Corridor

With Clothes / Between Two Persons / 500 mm Attached with String / repeated 5 times				With Clothes / Between Two Persons / 1000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	47	463		0	992	945
	1	486			1	1000	
	2	486			2	925	
	3	432			3	967	
1. Exp	4	521		1. Exp	4	1005	
	5	0			5	951	
	6	46			6	921	
	7	475			7	999	
	8	421			8	934	
	9	473			9	861	
	10	411			10	844	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	445	446		0	1048	937
	1	453			1	993	
	2	451			2	943	
	3	0			3	934	
2. Exp	4	47		2. Exp	4	931	
	5	0			5	905	
	6	46			6	892	
	7	395			7	948	
	8	476			8	938	
	9	457			9	870	
	10	442			10	905	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	521	512		0	0	879
	1	0			1	46	
	2	46			2	927	
	3	528			3	0	
3. Exp	4	0		3. Exp	4	47	
	5	47			5	0	
	6	508			6	47	
	7	512			7	897	
	8	496			8	892	
	9	493			9	881	
	10	525			10	800	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	449	472		0	954	905
	1	509			1	991	
	2	445			2	896	
	3	529			3	902	
4. Exp	4	448		4. Exp	4	877	
	5	0			5	911	
	6	47			6	933	
	7	447			7	892	
	8	471			8	912	
	9	524			9	800	
	10	423			10	889	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	472	477		0	949	903
	1	523			1	929	
	2	494			2	929	
	3	452			3	926	
5. Exp	4	506		5. Exp	4	910	
	5	0			5	977	
	6	47			6	925	
	7	506			7	0	
	8	484			8	884	
	9	399			9	734	
	10	455			10	866	

Table A 1. (continued)

With Clothes / Between Two Persons / 1500 mm Attached with String / repeated 5 times				With Clothes / Between Two Persons / 2000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	1294		0	0	0
	1	46			1	47	
	2	0			2	1964	
	3	47			3	0	
1. Exp	4	0		1. Exp	4	47	
	5	46			5	0	
	6	0			6	46	
	7	47			7	0	
	8	1328			8	47	
	9	1362			9	2894	
	10	1192			10	2755	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	47	1285		0	0	0
	1	1357			1	47	
	2	1413			2	0	
	3	0			3	42	
2. Exp	4	46		2. Exp	4	0	
	5	1297			5	47	
	6	1340			6	1841	
	7	1277			7	0	
	8	1248			8	46	
	9	1201			9	1788	
	10	1143			10	1811	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	1224		0	0	0
	1	47			1	42	
	2	0			2	0	
	3	46			3	43	
3. Exp	4	0		3. Exp	4	0	
	5	47			5	43	
	6	1397			6	0	
	7	0			7	43	
	8	0			8	0	
	9	1257			9	47	
	10	1018			10	1926	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	1412	1331		0	0	0
	1	1378			1	47	
	2	1419			2	0	
	3	1380			3	43	
4. Exp	4	0		4. Exp	4	0	
	5	51			5	42	
	6	1300			6	0	
	7	0			7	43	
	8	1237			8	0	
	9	1311			9	46	
	10	1210			10	1800	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	1494		0	0	0
	1	47			1	43	
	2	0			2	0	
	3	46			3	43	
5. Exp	4	1278		5. Exp	4	0	
	5	0			5	43	
	6	46			6	0	
	7	1283			7	42	
	8	1960			8	2360	
	9	1453			9	1612	
	10	46			10	0	

Table A 1. (continued)

With Clothes / Between Two Persons / 2500-3000-3500-4000 mm			
Attached with String / repeated 5 times			
1. Exp	Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	0
	1	42	
	2	0	
	3	43	
	4	0	
	5	43	
	6	0	
	7	42	
	8	0	
	9	43	
	10	0	
2. Exp	Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	0
	1	43	
	2	0	
	3	42	
	4	0	
	5	43	
	6	0	
	7	43	
	8	0	
	9	46	
	10	0	
3. Exp	Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	0
	1	42	
	2	0	
	3	43	
	4	0	
	5	43	
	6	0	
	7	42	
	8	0	
	9	43	
	10	0	
4. Exp	Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	0
	1	42	
	2	0	
	3	43	
	4	0	
	5	43	
	6	0	
	7	43	
	8	0	
	9	43	
	10	0	
5. Exp	Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	0
	1	43	
	2	0	
	3	43	
	4	0	
	5	42	
	6	0	
	7	43	
	8	0	
	9	0	
	10	0	

Table A 2. Raw Data of ‘Walking-Two Persons’ with Acrylic Sheet at Narrow Corridor

With Acrylic Sheet / Between Two Persons / 500 mm				With Acrylic Sheet / Between Two Persons / 1000 mm			
Attached with String / repeated 5 times				Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	51	550		0	1050	1043
	1	530			1	1047	
	2	514			2	1057	
	3	556			3	1027	
1. Exp	4	542		1. Exp	4	0	
	5	552			5	47	
	6	0			6	1115	
	7	47			7	1048	
	8	544			8	1040	
	9	603			9	982	
	10	561			10	1020	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	517	540		0	1059	989
	1	0			1	978	
	2	47			2	0	
	3	0			3	47	
2. Exp	4	47		2. Exp	4	958	
	5	586			5	1028	
	6	584			6	1005	
	7	544			7	1048	
	8	570			8	3212	
	9	487			9	1018	
	10	491			10	815	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	590	554		0	1012	1006
	1	567			1	1017	
	2	0			2	989	
	3	46			3	970	
3. Exp	4	554		3. Exp	4	910	
	5	565			5	1014	
	6	596			6	1098	
	7	544			7	1040	
	8	545			8	988	
	9	530			9	1040	
	10	496			10	992	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	504	521		0	1039	1003
	1	543			1	1023	
	2	519			2	957	
	3	530			3	977	
4. Exp	4	523		4. Exp	4	1041	
	5	531			5	1015	
	6	660			6	1001	
	7	526			7	1008	
	8	466			8	992	
	9	496			9	992	
	10	429			10	986	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	561	530		0	1044	983
	1	477			1	954	
	2	557			2	989	
	3	543			3	1004	
5. Exp	4	538		5. Exp	4	979	
	5	598			5	981	
	6	548			6	0	
	7	508			7	43	
	8	512			8	987	
	9	515			9	982	
	10	470			10	930	

Table A 2. (continued)

With Acrylic Sheet / Between Two Persons / 1500 mm Attached with String / repeated 5 times				With Acrylic Sheet / Between Two Persons / 2000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
1. Exp	0	43	1428	1. Exp	0	0	1984
	1	1447			1	42	
	2	1383			2	1986	
	3	0			3	1982	
	4	43			4	0	
	5	0			5	42	
	6	42			6	0	
	7	0			7	43	
	8	1482			8	0	
	9	1399			9	42	
	10	0			10	2818	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
2. Exp	0	0	1486	2. Exp	0	0	0
	1	42			1	43	
	2	1489			2	0	
	3	0			3	43	
	4	43			4	0	
	5	1501			5	42	
	6	1513			6	0	
	7	0			7	43	
	8	43			8	0	
	9	1442			9	3291	
	10	0			10	1934	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
3. Exp	0	0	1431	3. Exp	0	0	0
	1	43			1	43	
	2	1438			2	0	
	3	0			3	43	
	4	43			4	0	
	5	1421			5	43	
	6	0			6	0	
	7	43			7	42	
	8	1568			8	0	
	9	1376			9	43	
	10	1350			10	2128	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
4. Exp	0	0	1418	4. Exp	0	0	0
	1	42			1	43	
	2	0			2	0	
	3	43			3	42	
	4	0			4	0	
	5	43			5	43	
	6	1383			6	2344	
	7	0			7	0	
	8	43			8	43	
	9	1433			9	0	
	10	1437			10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
5. Exp	0	0	1336	5. Exp	0	43	0
	1	43			1	0	
	2	1382			2	43	
	3	0			3	0	
	4	43			4	0	
	5	0			5	1980	
	6	42			6	0	
	7	0			7	0	
	8	43			8	0	
	9	3023			9	0	
	10	1289			10	0	

Table A 2. (continued)

With Acrylic Sheet / Between Two Persons / 2500-3000-3500-4000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)
1. Exp	0	42	0
	1	0	
	2	43	
	3	0	
	4	43	
	5	0	
	6	43	
	7	0	
	8	42	
	9	0	
	10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
2. Exp	0	2471	0
	1	0	
	2	43	
	3	0	
	4	43	
	5	0	
	6	43	
	7	0	
	8	42	
	9	0	
	10	43	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
3. Exp	0	0	0
	1	43	
	2	0	
	3	42	
	4	0	
	5	42	
	6	2440	
	7	0	
	8	43	
	9	3268	
	10	3095	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
4. Exp	0	0	0
	1	43	
	2	0	
	3	43	
	4	0	
	5	42	
	6	0	
	7	43	
	8	0	
	9	0	
	10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
5. Exp	0	0	0
	1	47	
	2	0	
	3	42	
	4	0	
	5	47	
	6	0	
	7	43	
	8	0	
	9	43	
	10	3208	

Table A 3. Summary of Results of ‘Walking-Two Persons’ with Clothes at Narrow Corridor

SUMMARY - WALKING TWO PERSONS - ON CLOTHES																				
Distance Between Two Persons (mm)	500					1000					1500					2000				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
# of '0' or unreliable values over 11 steps	3	4	4	2	2	none	none	6	none	1	8	3	8	3	7	all	all	all	all	all
Average Distance (mm)	463	446	512	472	477	945	937	879	905	903	1294	1285	1224	1331	1494	0	0	0	0	0
Distance Between Two Persons (mm)	2500					3000					3500					4000				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
# of '0' or unreliable values over 11	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all
Average Distance (mm)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A 4. Summary of Results of ‘Walking-Two Persons’ with Acrylic Sheet at Narrow Corridor

SUMMARY - WALKING TWO PERSONS - ON ACRYLIC SHEET																				
Distance Between Two Persons (mm)	500					1000					1500					2000				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
# of '0' or unreliable values over 11	3	4	2	none	none	2	3	none	none	2	7	7	5	8	9	9	all	all	all	all
Average Distance (mm)	550	540	554	521	530	1043	989	1006	1003	983	1428	1486	1431	1418	1336	1984	0	0	0	0
Distance Between Two Persons (mm)	2500					3000					3500					4000				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
# of '0' or unreliable values over 11	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all
Average Distance (mm)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A 5. Raw Data of ‘Walking-Two Persons’ with Clothes at Wider Corridor

With Clothes / Between Two Persons / 500 mm				With Clothes / Between Two Persons / 1000 mm			
Attached with String / repeated 5 times				Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	564		0	940	933
	1	51			1	930	
	2	0			2	950	
	3	50			3	874	
1. Exp	4	566		1. Exp	4	880	
	5	0			5	928	
	6	51			6	947	
	7	542			7	947	
	8	553			8	928	
	9	593			9	995	
	10	567			10	948	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	531		0	962	966
	1	50			1	1040	
	2	548			2	969	
	3	0			3	1031	
2. Exp	4	51		2. Exp	4	893	
	5	525			5	916	
	6	0			6	969	
	7	50			7	943	
	8	0			8	1000	
	9	574			9	961	
	10	476			10	938	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	489	477		0	0	945
	1	481			1	1034	
	2	454			2	885	
	3	0			3	922	
3. Exp	4	50		3. Exp	4	1063	
	5	0			5	940	
	6	51			6	970	
	7	0			7	930	
	8	51			8	884	
	9	0			9	900	
	10	485			10	924	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	50	476		0	989	962
	1	0			1	979	
	2	51			2	1003	
	3	479			3	911	
4. Exp	4	465		4. Exp	4	910	
	5	471			5	1013	
	6	0			6	1009	
	7	50			7	981	
	8	516			8	951	
	9	516			9	954	
	10	408			10	879	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	494		0	968	953
	1	51			1	920	
	2	484			2	881	
	3	510			3	918	
5. Exp	4	0		5. Exp	4	980	
	5	51			5	965	
	6	493			6	931	
	7	490			7	1028	
	8	0			8	952	
	9	50			9	969	
	10	0			10	974	

Table A 5. (continued)

With Clothes / Between Two Persons / 1500 mm Attached with String / repeated 5 times				With Clothes / Between Two Persons / 2000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
1. Exp	0	0	1451	1. Exp	0	0	0
	1	51			1	50	
	2	1485			2	0	
	3	1429			3	51	
	4	1531			4	0	
	5	1429			5	0	
	6	1382			6	0	
	7	0			7	51	
	8	46			8	0	
	9	3134			9	47	
	10	2324			10	3213	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
2. Exp	0	1551	1452	2. Exp	0	0	0
	1	1515			1	51	
	2	0			2	0	
	3	1378			3	0	
	4	1434			4	1521	
	5	1365			5	0	
	6	1467			6	0	
	7	0			7	47	
	8	50			8	1947	
	9	3217			9	0	
	10	2339			10	46	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
3. Exp	0	0	1459	3. Exp	0	0	0
	1	51			1	47	
	2	1448			2	0	
	3	1435			3	51	
	4	0			4	1813	
	5	1459			5	0	
	6	0			6	0	
	7	1481			7	47	
	8	1540			8	0	
	9	0			9	50	
	10	1393			10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
4. Exp	0	51	1431	4. Exp	0	0	1891
	1	1431			1	50	
	2	0			2	0	
	3	55			3	51	
	4	1463			4	1858	
	5	1400			5	0	
	6	0			6	51	
	7	55			7	1924	
	8	0			8	0	
	9	54			9	46	
	10	2409			10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
5. Exp	0	1503	1361	5. Exp	0	0	1872
	1	1438			1	51	
	2	0			2	0	
	3	50			3	51	
	4	1271			4	0	
	5	1250			5	0	
	6	0			6	0	
	7	50			7	1903	
	8	1304			8	1924	
	9	1378			9	1809	
	10	1380			10	1853	

Table A 5. (continued)

With Clothes / Between Two Persons / 2500-3000-3500-4000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)
1. Exp	0	0	0
	1	55	
	2	0	
	3	55	
	4	0	
	5	0	
	6	54	
	7	0	
	8	55	
	9	0	
	10	55	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
2. Exp	0	0	0
	1	50	
	2	0	
	3	51	
	4	0	
	5	1068	
	6	0	
	7	50	
	8	0	
	9	51	
	10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
3. Exp	0	0	0
	1	47	
	2	0	
	3	50	
	4	0	
	5	51	
	6	0	
	7	51	
	8	0	
	9	50	
	10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
4. Exp	0	0	0
	1	50	
	2	0	
	3	51	
	4	0	
	5	51	
	6	0	
	7	50	
	8	0	
	9	51	
	10	3209	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
5. Exp	0	0	0
	1	51	
	2	0	
	3	50	
	4	2395	
	5	0	
	6	0	
	7	50	
	8	0	
	9	51	
	10	3201	

Table A 6. Raw Data of 'Walking-Two Persons' with Acrylic Sheet at Wider Corridor

With Acrylic Sheet / Between Two Persons / 500 mm Attached with String / repeated 5 times				With Acrylic Sheet / Between Two Persons / 1000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	570		0	1051	1006
	1	47			1	1047	
	2	592			2	960	
	3	625			3	1050	
1. Exp	4	0		1. Exp	4	0	
	5	47			5	47	
	6	590			6	964	
	7	511			7	1094	
	8	0			8	975	
	9	47			9	969	
	10	532			10	940	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	46	545		0	964	917
	1	582			1	922	
	2	0			2	0	
	3	47			3	47	
2. Exp	4	581		2. Exp	4	915	
	5	552			5	914	
	6	0			6	897	
	7	47			7	945	
	8	0			8	952	
	9	523			9	911	
	10	485			10	836	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	574		0	1013	1002
	1	47			1	1067	
	2	0			2	1009	
	3	46			3	0	
3. Exp	4	565		3. Exp	4	47	
	5	0			5	0	
	6	47			6	43	
	7	0			7	998	
	8	46			8	948	
	9	582			9	976	
	10	0			10	2127	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	609	548		0	1073	982
	1	0			1	987	
	2	46			2	940	
	3	520			3	975	
4. Exp	4	0		4. Exp	4	958	
	5	47			5	963	
	6	0			6	967	
	7	520			7	982	
	8	562			8	993	
	9	555			9	0	
	10	521			10	984	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	0	573		0	978	976
	1	46			1	966	
	2	0			2	948	
	3	47			3	1030	
5. Exp	4	593		5. Exp	4	985	
	5	588			5	0	
	6	539			6	47	
	7	0			7	981	
	8	43			8	977	
	9	0			9	965	
	10	46			10	952	

Table A 6. (continued)

With Acrylic Sheet / Between Two Persons / 1500 mm Attached with String / repeated 5 times				With Acrylic Sheet / Between Two Persons / 2000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	1520	1479		0	0	0
	1	1456			1	47	
	2	1457			2	0	
	3	1488			3	47	
1. Exp	4	0		1. Exp	4	0	
	5	47			5	47	
	6	1484			6	0	
	7	1471			7	43	
	8	0			8	0	
	9	46			9	43	
	10	0			10	1940	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	1535	1469		0	0	0
	1	1494			1	47	
	2	1471			2	0	
	3	1458			3	47	
2. Exp	4	0		2. Exp	4	0	
	5	47			5	47	
	6	1465			6	1835	
	7	1468			7	0	
	8	0			8	47	
	9	1491			9	0	
	10	1366			10	43	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	1476	1438		0	0	0
	1	1446			1	46	
	2	0			2	0	
	3	47			3	47	
3. Exp	4	0		3. Exp	4	0	
	5	43			5	42	
	6	1389			6	1882	
	7	0			7	0	
	8	46			8	46	
	9	1458			9	0	
	10	1422			10	43	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	47	1432		0	0	0
	1	1453			1	46	
	2	0			2	0	
	3	43			3	47	
4. Exp	4	1423		4. Exp	4	0	
	5	1422			5	47	
	6	0			6	0	
	7	46			7	42	
	8	1402			8	0	
	9	1459			9	47	
	10	2750			10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	1525	1403		0	0	0
	1	0			1	47	
	2	47			2	0	
	3	1426			3	47	
5. Exp	4	1352		5. Exp	4	0	
	5	1388			5	42	
	6	0			6	0	
	7	42			7	43	
	8	0			8	0	
	9	47			9	47	
	10	1322			10	2998	

Table A 6. (continued)

With Acrylic Sheet / Between Two Persons / 2500-3000-3500-4000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)
1. Exp	0	0	0
	1	43	
	2	0	
	3	46	
	4	0	
	5	0	
	6	0	
	7	0	
	8	42	
	9	0	
	10	43	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
2. Exp	0	0	0
	1	50	
	2	0	
	3	51	
	4	0	
	5	51	
	6	0	
	7	50	
	8	0	
	9	51	
	10	3174	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
3. Exp	0	0	0
	1	50	
	2	0	
	3	50	
	4	0	
	5	51	
	6	0	
	7	47	
	8	0	
	9	50	
	10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
4. Exp	0	51	0
	1	0	
	2	51	
	3	0	
	4	51	
	5	0	
	6	50	
	7	0	
	8	47	
	9	0	
	10	42	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
5. Exp	0	0	0
	1	51	
	2	0	
	3	46	
	4	0	
	5	47	
	6	0	
	7	47	
	8	0	
	9	47	
	10	0	

Table A 7. Summary of Results of ‘Walking-Two Persons’ with Clothes at Wider Corridor

SUMMARY - WALKING TWO PERSONS - ON CLOTHES																				
Distance Between Two Persons (mm)	500					1000					1500					2000				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
# of '0' or unreliable values over 11	6	7	7	5	7	none	none	1	none	none	6	5	5	8	4	all	all	all	9	7
Average Distance (mm)	564	531	477	476	494	933	966	945	962	953	1451	1452	1459	1431	1361	0	0	0	1891	1872
Distance Between Two Persons (mm)	2500					3000					3500					4000				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
# of '0' or unreliable values over 11	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all
Average Distance (mm)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A 8. Summary of Results of ‘Walking-Two Persons’ with Acrylic Sheet at Wider Corridor

SUMMARY - WALKING TWO PERSONS - ON ACRYLIC SHEET																				
Distance Between Two Persons (mm)	500					1000					1500					2000				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
# of '0' or unreliable values over 11	6	6	9	5	8	2	2	5	1	2	5	3	6	6	6	all	all	all	all	all
Average Distance (mm)	570	545	574	548	573	1006	917	1002	982	976	1479	1469	1438	1432	1403	0	0	0	0	0
Distance Between Two Persons (mm)	2500					3000					3500					4000				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
# of '0' or unreliable values over 11 steps	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all	all
Average Distance (mm)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A 9. Raw Data of 'Walking-Two Persons-Back' at Wider Corridor

Acrylic Sheet BACK / Between Two Persons / 500 mm Attached with String / repeated 5 times				Acrylic Sheet BACK / Between Two Persons / 1000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	463	476		0	1000	949
	1	453			1	975	
	2	457			2	965	
	3	500			3	964	
1. Exp	4	483		1. Exp	4	947	
	5	477			5	937	
	6	490			6	911	
	7	469			7	946	
	8	487			8	923	
	9	471			9	937	
	10	489			10	937	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	489	487		0	989	953
	1	502			1	979	
	2	485			2	976	
	3	502			3	948	
2. Exp	4	475		2. Exp	4	918	
	5	500			5	962	
	6	476			6	933	
	7	494			7	914	
	8	478			8	951	
	9	497			9	963	
	10	457			10	953	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	494	490		0	1011	943
	1	500			1	957	
	2	488			2	918	
	3	490			3	945	
3. Exp	4	503		3. Exp	4	935	
	5	479			5	932	
	6	487			6	928	
	7	474			7	933	
	8	492			8	931	
	9	502			9	935	
	10	481			10	950	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	485	488		0	979	940
	1	456			1	962	
	2	494			2	966	
	3	473			3	974	
4. Exp	4	493		4. Exp	4	978	
	5	480			5	950	
	6	489			6	977	
	7	503			7	911	
	8	518			8	863	
	9	495			9	882	
	10	485			10	899	
	Time (s)	Measured Distance (mm)	Average Distance (mm)		Time (s)	Measured Distance (mm)	Average Distance (mm)
	0	517	494		0	1077	965
	1	473			1	1000	
	2	500			2	986	
	3	500			3	959	
5. Exp	4	487		5. Exp	4	950	
	5	494			5	974	
	6	496			6	948	
	7	513			7	942	
	8	508			8	919	
	9	487			9	933	
	10	455			10	930	

Table A 9. (continued)

Acrylic Sheet BACK / Between Two Persons / 1500 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)
1. Exp	0	1462	1421
	1	1407	
	2	1423	
	3	1466	
	4	1388	
	5	1446	
	6	1455	
	7	1397	
	8	1395	
	9	1418	
	10	1377	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
2. Exp	0	1505	1448
	1	1427	
	2	1422	
	3	1421	
	4	1506	
	5	1425	
	6	1432	
	7	1416	
	8	1457	
	9	1432	
	10	1490	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
3. Exp	0	0	1463
	1	1447	
	2	1498	
	3	1480	
	4	1428	
	5	1489	
	6	1452	
	7	1467	
	8	1441	
	9	1518	
	10	1413	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
4. Exp	0	1468	1452
	1	1473	
	2	1466	
	3	1456	
	4	1477	
	5	1452	
	6	1423	
	7	1451	
	8	1451	
	9	1442	
	10	1411	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
5. Exp	0	1496	1429
	1	1451	
	2	1465	
	3	1423	
	4	1373	
	5	1397	
	6	1420	
	7	1409	
	8	1440	
	9	1416	
	10	1430	

Acrylic Sheet BACK / Between Two Persons / 2000 mm Attached with String / repeated 5 times			
	Time (s)	Measured Distance (mm)	Average Distance (mm)
1. Exp	0	0	1970
	1	1987	
	2	1935	
	3	0	
	4	0	
	5	2003	
	6	0	
	7	1966	
	8	1957	
	9	0	
	10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
2. Exp	0	0	1943
	1	50	
	2	0	
	3	50	
	4	1926	
	5	1954	
	6	1911	
	7	1967	
	8	1951	
	9	1951	
	10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
3. Exp	0	0	1962
	1	47	
	2	1967	
	3	1956	
	4	1942	
	5	1984	
	6	1935	
	7	1957	
	8	1990	
	9	0	
	10	47	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
4. Exp	0	1994	1968
	1	1974	
	2	1980	
	3	1932	
	4	1958	
	5	0	
	6	47	
	7	1960	
	8	1975	
	9	1971	
	10	0	
	Time (s)	Measured Distance (mm)	Average Distance (mm)
5. Exp	0	2033	1975
	1	1960	
	2	1928	
	3	1954	
	4	1918	
	5	2019	
	6	47	
	7	0	
	8	50	
	9	1970	
	10	2014	

Table A 10. Summary of Results of 'Walking-Two Persons-Back' at Wider Corridor

SUMMARY - WALKING TWO PERSONS - BACK																				
Distance Between Two Persons (mm)	500					1000					1500					2000				
	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
# of '0' or unreliable values over 11 steps	none	none	none	none	none	none	none	none	none	none	none	none	1	none	none	6	5	4	3	3
Average Distance (mm)	476	487	490	488	494	949	953	943	940	965	1421	1448	1463	1452	1429	1970	1943	1962	1968	1975

Appendix B – Group Experiments

Table B 1. Raw Data of Group Experiment No.1 (d: 0.5 m)

Inter-person Distance : 500 mm								
1. Experiment			2. Experiment			3. Experiment		
Time (s)	Measured Distance (mm)	Average Distance (mm)	Time (s)	Measured Distance (mm)	Average Distance (mm)	Time (s)	Measured Distance (mm)	Average Distance (mm)
0	190	279	0	435	366	0	469	385
1	200		1	355		1	395	
2	212		2	257		2	420	
3	187		3	308		3	433	
4	239		4	349		4	452	
5	280		5	325		5	415	
6	318		6	355		6	445	
7	238		7	402		7	432	
8	287		8	403		8	393	
9	277		9	389		9	406	
10	286		10	359		10	389	
11	320		11	338		11	410	
12	286		12	379		12	405	
13	330		13	354		13	358	
14	330		14	378		14	338	
15	287		15	359		15	354	
16	294		16	342		16	366	
17	325		17	378		17	377	
18	322		18	387		18	369	
19	317		19	401		19	364	
20	304		20	399		20	370	
21	287		21	400		21	351	
22	296					22	321	
						23	332	
						24	312	
						25	341	

Table B 2. Raw Data of Group Experiment No.2 (d: 1 m)

Inter-person Distance : 1000 mm								
1. Experiment			2. Experiment			3. Experiment		
Time (s)	Measured Distance (mm)	Average Distance (mm)	Time (s)	Measured Distance (mm)	Average Distance (mm)	Time (s)	Measured Distance (mm)	Average Distance (mm)
0	947	898	0	758	779	0	775	778
1	876		1	793		1	825	
2	921		2	784		2	799	
3	905		3	762		3	819	
4	914		4	699		4	788	
5	874		5	767		5	779	
6	903		6	806		6	763	
7	900		7	823		7	733	
8	833		8	845		8	754	
9	888		9	750		9	741	
10	913							

Table B 3. Raw Data of Group Experiment No.3 (d: 1.5 m)

Inter-person Distance : 1500 mm								
1. Experiment			2. Experiment			3. Experiment		
Time (s)	Measured Distance (mm)	Average Distance (mm)	Time (s)	Measured Distance (mm)	Average Distance (mm)	Time (s)	Measured Distance (mm)	Average Distance (mm)
0	1469	1416	0	1423	1330	0	1461	1419
1	1498		1	1420		1	1467	
2	1411		2	1410		2	1412	
3	1416		3	1373		3	1398	
4	1428		4	1326		4	1413	
5	1451		5	1408		5	1441	
6	1402		6	1349		6	1396	
7	1384		7	1206		7	1360	
8	1284		8	1054				

Table B 4. Raw Data of Group Experiment No.4 (d: 2 m)

Inter-person Distance : 2000 mm								
1. Experiment			2. Experiment			3. Experiment		
Time (s)	Measured Distance (mm)	Average Distance (mm)	Time (s)	Measured Distance (mm)	Average Distance (mm)	Time (s)	Measured Distance (mm)	Average Distance (mm)
0	0	1947	0	50	1885	0	1973	1957
1	1996		1	0		1	1940	
2	2004		2	1874		2	1981	
3	1920		3	1889		3	1956	
4	1933		4	1994		4	2000	
5	1952		5	1927		5	0	
6	1879		6	1906		6	46	
7	0		7	1718		7	1891	