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A comparison between robot gait and human gait with the help of literature research and Gait Analysis of the Nao Robot H25

2011

Undergraduate Research PEERS -

University College Maastricht

Acknowledgements

This paper is the result of six months of hard work and determination, but I cannot take all the credit for it. Many people have helped me out the last 6 months, with words of support or advice, with constructive feedback, with fruitful discussions, or just without words but with a smile. Without these people I would not have pulled it off, so thank you! Particularly, I would like to thank all the following people for their help:

- Nico Roos, my coordinator, for his ongoing interest, constructive feedback and help whenever I needed it.
- Kenneth Meijer, for opening up possibilities to do robot Gait Analysis and his help especially concerning human kinesiology.
- Paul Willems, for looking at the data, brainstorming what the best way was to approach this data and his patience towards me.
- Lonneke Bevers, for her good tips and stimulating words during all the PEERS sessions.
- Oscar van den Wijngaard, for his continuous energy and trust in the research.

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1. Introduction

Already in the times of Leonardo Da Vinci the idea for the creation of humanoid robots arose. Da Vinci sketched plans and exhaustive drawings for his so called 'Leonardo's robot', a robot that was able to move its head and jaw, wave its arm and sit up [1]. From that moment human interest for robotics was born. Nowadays industrial, educational and commercial robots are widely available and several companies are specialized in the development of these robots. Where educational robots are mainly used for instructional purposes at universities, industrial robots are performing numerous vital jobs. They are used in for example manufacturing, assembling, packing and assisting in surgeries. Most of these robots work with greater precision and cheaper than human beings, and thus offer a large range of beneficial opportunities for future use [2].

When developing robots, one of the most important issues that need to be taken into account is the kinesiology of the robot, in other words, the way a robot moves around. Robot motion, and in specific robot walking, can be seen as the basis for robot development. Although robots that are unable to walk can certainly be valuable, the ability to walk increases the overall utility of a robot. Hence, walking seems to be a fundamental feature of most robots and can be seen as a very important feature for their further development and use. The entire aim of robot walking is to achieve human-like walking, but is this aim not too idealistic?

Although achieving human-like motion is a challenging aim, most robots have succeeded in reaching a kind of human-like motion. Their walking pattern is almost identical to the walking pattern human beings employ. During walking two different phases arise in sequence (see figure 1). All walking patterns start with a stable double support phase in which both feet support the rest of the body. This phase is followed by a more unstable single support phase in which only one of the legs remains in contact with the ground while the other leg commences the walk. Then, a second double support phase takes place, ensuring stability halfway the walking pattern. Next, there is another single support phase in which the other leg than before supports the body. Finally, the walking pattern is completed by a double support phase, bringing the robot back to its original position one step ahead of where the walk started. From this position another walking pattern can be initiated. So, in both robots and humans there is regular interchangeability of single and double support phases. This is not the only thing that robot walking has in common with human walking. Gait repeatability, the ability to reproduce a similar walking pattern over and over again, is another characteristic of both robot and human walking. In addition, both humans and robots have the ability to use joint-like structures, known under the name of 'degrees of freedoms' in robots [3].

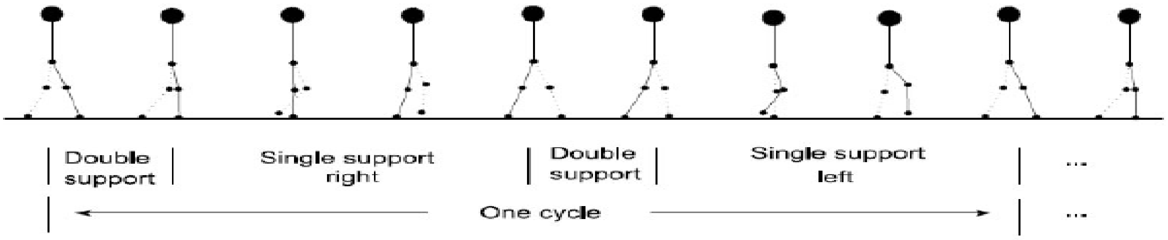

Figure 1: One of the similarities between robot and human walking is their walking pattern, also called gait. In both cases the walking patterns starts with a stable double support phase, followed by a single support phase in which the right foot supports the body. Halfway the step another double support phase occurs to re-ensure stability. Then, another single support phase followed, this time in which the left foot supports the rest of the body. The gait is finished by another double support phase [4].

Although most robots succeed in creating a form of human, multidirectional, bipedal walking, many difficulties remain present. One of the major drawbacks for robot motion is maintaining stability during walking. Especially when the walking speed is increasing, many robots seem to struggle to remain stable while walking. An uneven ground or a moderate touch of a hand can already lead to a robot losing its stability and falling over. While human beings can continuously adjust their movements to the changing environment and receive feedback from their muscular system while they move, robots cannot reap the fruits of feedback as such. The hardware of a robot cannot be modified so everything needs to be incorporated prior to the commencement of developing robot motion. Prior to this development, one needs to think about things like how to achieve robot motion efficiently and how to ensure and maintain stability while walking but also about the possible feedback mechanisms that are needed in order to achieve these goals [4].

This paper will focus on the walking pattern of both robots as well as human beings by answering the problem statement: To what extent can the robot gait be compared to the human gait? This question will be answered with the help of a number of research questions, which will be discussed subsequently. Before that, the importance of this paper will be emphasized. Then, a literature review will be given that analyzes what the human gait exactly is and which dynamic principles count for human walking. This will be followed by a literature review examining the general differences between robot and human walking. Next, the experiment will focus on one robot in specific, the Nao H25, which will be explained in more detail later. In the experiment the strengths and limitations of the walking pattern of the Nao will be brought to light and analyzed. The central research question in the experiment is: To what extent does the Nao follow the same dynamic principles as the human during walking? Afterwards, a conclusion will recap the most important findings from the literature research and the experiment in order to find an answer to the problem statement: To what extent can the robot gait be compared with the human gait? Finally, a discussion will elaborate on the implications of the results of the study, show potential limitations and offer ideas for future research in the field of robotic kinesiology.

2. The importance of this paper

The purposes of this study are plentiful. On the one hand, this study aims at discovering the way the Nao Robot adopts a walking pattern. On the other hand, it also functions to put these findings in a broader perspective with the help of a literature review about human and robot walking in general and the dynamic principles that are important in this matter. Although this paper might not necessarily bring new knowledge to the field of kinesiology and robotics, it does certainly succeed in shedding new light on both fields. This paper broadens the current view on robotics by offering a completely new perspective for looking at robot motion.

Whereas most studies in the field of robotics are focused on the mathematical algorithms behind robot motion, this paper shifts its focus more to the kinesiologic perspective on robot motion. Instead of examining whether the software currently used in robotics can be effectively proven in practice, this paper will analyze robot motion with the help of Gait Analysis. Gait Analysis is a tool to examine the walking pattern, also known as gait, of human beings. It can be seen to play a crucial role in the field of rehabilitation and can, for example, function to regain stability and normal walking patterns in humans with dysfunctions [5].

Gait Analysis opens up opportunities to discover the strengths and limitations of the walking pattern of a robot, by analyzing values such as the ‘ground reaction forces’ and the ‘centre of mass’. Because this tool is mostly used to measure the walking pattern of human beings, the data from Gait Analysis in robots allow for an excellent comparison between the walking pattern of human beings and robots. Generally, the walking pattern of robots is being analyzed by looking at the development of the robot and the intentions of the producers. By examining the development of the robot, one can draw conclusions about the kinematics of the robot. However, in this paper, the walking pattern will be analyzed in a completely different manner, namely by looking at the end product (the robot) instead of at the starting point of the development (the algorithms). By doing so, interesting conclusions can be drawn about important concepts in the kinesiology, such as stability and the robot gait. These conclusions can be seen as feedback in order to improve the robot and might prove exceptionally useful in the future development of robotics.

Naturally, one can already give feedback about the robot by examining what works efficiently and by analyzing in which way the robot is dysfunctioning. However, this information is of little use for the future development of robotics as it only says something about the mistake itself, not about the origin of the mistake. For this reason, the findings in this paper will be much more valuable, as they draw conclusions about the source of the mistake and are able to unveil the exact cause of instability or an inconsequent walking pattern, for example.

3. Literature review

3.1 What is the human gait and which dynamic principles count for human walking?

In order to look at the exact differences between the robot and human gait, it is important to know some basics about human motion first. Hence, in this part will be explained what the human gait actually is and how humans adopt a certain gait. Relating to the last question are the dynamic principles that count for walking. Although most humans learn to walk effortlessly at a young age, walking is far from effortless for the body. The body continuously needs to take certain principles into account when walking. During walking, the body, for example, needs to keep track of the centre of mass and needs to ensure that the centre of mass does not fall outside the base of support in which case instability would occur. All these different dynamic terms and principles important for walking will be discussed in this section of the paper.

3.1.1 The human gait

As mentioned in the introduction, the human gait consists of two distinct phases: a single limb-support phase, in which the body is supported by one leg, and a double-limb support phase, in which the body is supported by two legs. One human gait, or one walking cycle, consists of two double-limb support and two single-limb support phases.

During this cycle, body weight is being shifted from the one leg to the other leg. An important concept related to body weight is the so called 'centre of mass' (COM), also called 'centre of gravity' (COG). Both terms are used to describe the point of the body where the mass of the body is concentrated. At this point, all the rotary forces on the body are balanced. It is generally accepted for human beings that the COM is situated at 57% of the standing height in males and 55% of the standing height in females. During the double-limb support phase the COM remains constantly fixed at this point, as stability is ensured due to the body being supported by both legs. In the single-limb support phase, however, the COM shifts to the stance leg and becomes about parallel to this leg. As the moving leg is not in contact with the ground, the mass is purely concentrated on the stance leg and the COM shifts to this leg. Also, the height of the COM increases during single-limb support phase as the same amount of mass is supported by one leg instead of two causing the COM to be moved more towards the upper body [5].

During normal gait, the COM moves in a smooth sinusoidal pattern in both the horizontal and vertical planes (see figure 2). This sinusoidal pattern results from the fact that the COM shifts around during the walking cycle. During the double-limb support phase the COM is relatively low and in the centre of the body, whereas during the single-limb support phase the COM is somewhat higher and parallel to the stance leg. This leads to a sinusoidal pattern of COM displacement [6].

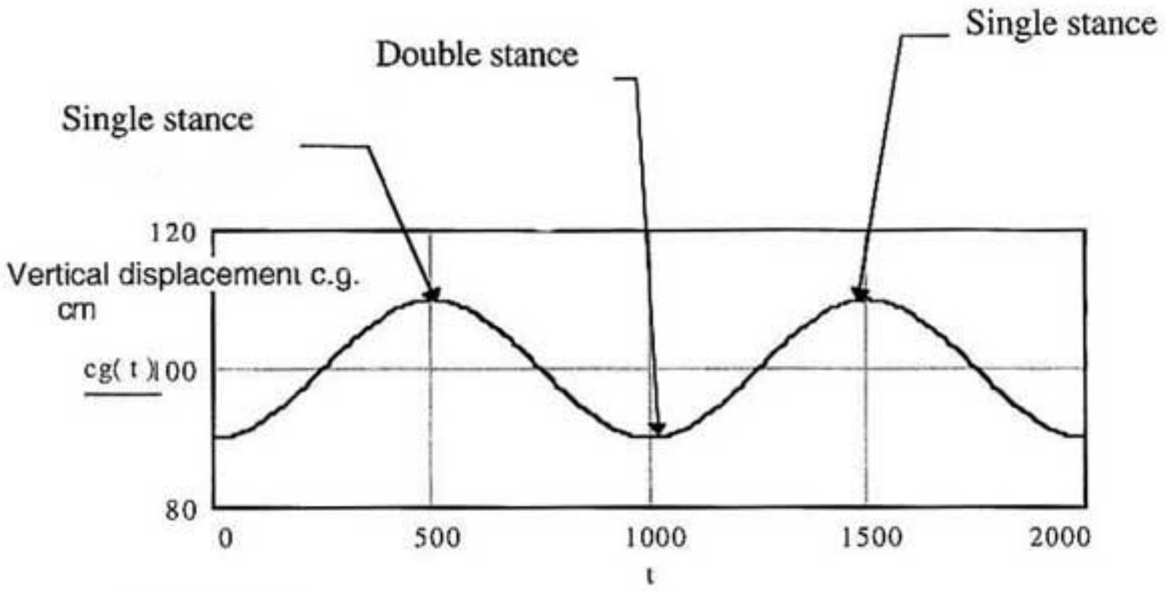

Figure 2: This graph shows the sinusoidal pattern of the vertical displacement of the COM/COG during one gait. Noticeable is that the COM has the highest vertical displacement during the single stance (single-limb support phase) as all mass is supported by one leg. The lowest vertical displacement occurs during the double stance (double-limb support phase) as the mass is supported by both legs [6].

As already mentioned above, the centre of mass can also be called the centre of gravity. As the centre of mass describes the point of a body where the mass is concentrated, it also describes the point from which a gravitational force acts downwards. Except from this internal force, there are also external forces acting on the body during walking, such as the ground reaction force (GRF). The ground reaction force is formed when the foot is in contact with the ground in response to the gravitational force acting on the ground. As a result, a ground reaction force is developed that is equal and opposite to the force the foot applies to the ground, in other words the gravitational force (see figure 3) [6].

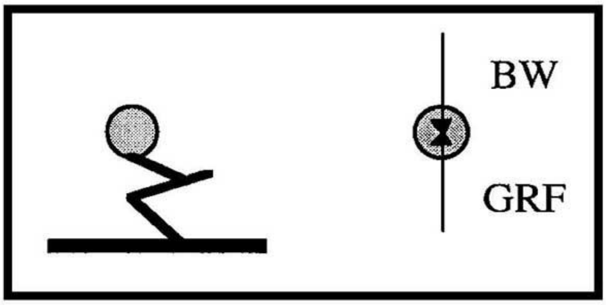

Figure 3: When standing still the gravitational force acting downwards (here called BW) is equal but opposite to the ground reaction force acting upwards (GRF) [6].

The point from which the ground reaction force acts is called the centre of pressure (COP), as the external pressure applied on the body acts from this point. Just like the COM, the COP changes position during gait. Whereas the COP is situated at the rear of the foot during double stance phase, the COP moves anterior during single stance phase while the foot pushes off from the ground. Not only does the position of the COP change around during gait, but also the value of the GRF formed at the COP changes (see figure 4). During double stance phase the GRF reaches its maximum of about 120% of the body weight of the person, as it acts in response to a large gravitational force acting from two feet. The GRF drops to about 80% of the body weight during single stance phase, as there is a smaller force acting on the ground from one leg allowing a smaller GRF to be formed [6].

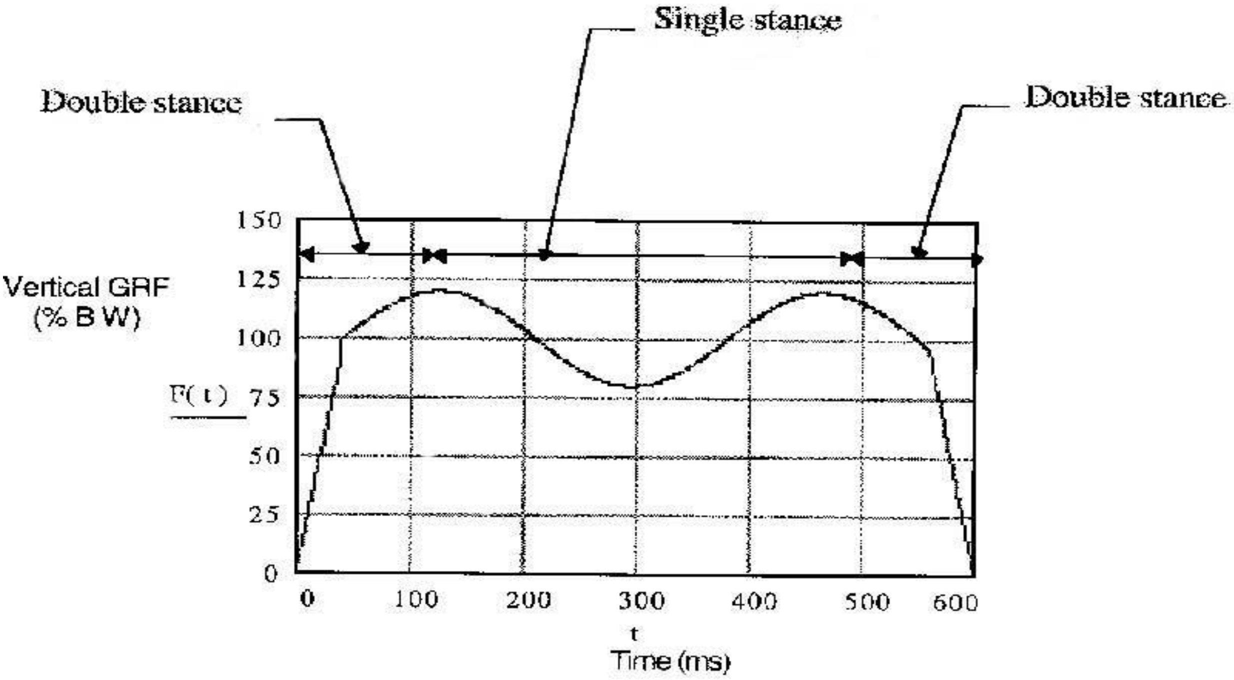

Figure 4: The value of the GRF does not remain constant during one gait. It reaches its maximum during double stance but drops to a minimum during single stance [6].

In any case, the COP position is limited to the base of support, the area between and below the feet (see figure 5). The reason for this is that the ground reaction force is the product of a pressure distribution under the feet. In other words, the feet have to be in contact with the ground in order for the ground reaction force to be formed [7].

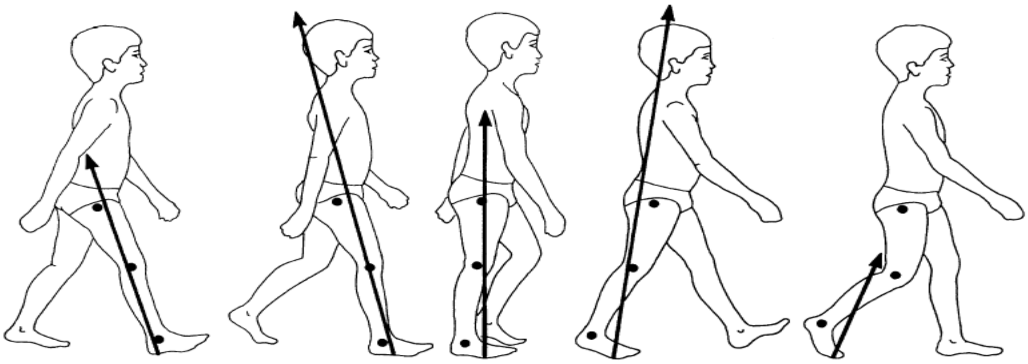

Figure 5: As there is always a gravitational force acting downwards, there is also always a ground reaction force acting upwards. This picture shows the GRF vector during double stance and single stance. Not only does the value of the force

move around during gait, but also the position from which the GRF acts shifts position (COP). Nevertheless, the COP is always limited to the base of support [8].

In conclusion, there is a gravitational force acting from the centre of mass on the ground and a ground reaction force acting from the centre of pressure on the body. During stance (standing completely still) both of these forces are equal and opposite to each other, thus resulting in a total force of 0. The total force acting on a body is exceptionally important, as it is strongly connected to the moment of force acting on the same body. The moment of force is the tendency of a force to rotate an object around a certain axis. It can also be seen as a twist or a pull. A moment can be calculated by taking the product of the force itself and its arm, known as the perpendicular distance from the point of rotation (the axis going through the COM and COP) to the point where the force is acting. In simple words, a moment can be calculated by using the formula $M_o = r_{OF} \times F$ in which M_0 represents the moment, r_{OF} represents the arm of the force and F the force itself [9]. Consequently, when the total force is 0 during stance, the total moment is also 0, thus resulting in no tendency whatsoever to twist around. For this reason, stance is seen as a stable phase in which stability is maintained completely [6].

However, only during stance the total moment is 0 and the body is completely stable. During gait, on the other hand, the forces are often unbalanced. Newton's second law states that when a force is unbalanced, the force must equal the mass times the acceleration. In other words, when the acceleration is positive, the force must be bigger than the mass. So when the total force during gait is above 0 N, this means that the ground reaction force is larger than the gravitational force, the result is positive acceleration and positive work on the COM. Such a positive acceleration occurs when the COM is at its lowest point during double-limb support phase and largely compensates for the negative work on the COM afterwards. The acceleration becomes negative when the COM is at its highest point during the single-limb support phase [6].

Humans begin the negative work over a so called collision phase, a phase that begins at heel-strike and extends slightly beyond double-limb support phase. The collision phase is called this way because of the collision of the leading leg with the ground. A large part of the negative work or acceleration during the collision phase is due to the flexion of the knee, although the soft tissues seem to play a role in it as well. The collision phase is followed by a rebound phase. In this phase the leading leg performs positive work in order to straighten the leg. Once again, the knee is crucial during this phase, as it accounts for most of the rebound work. This is most probably due to both active muscle and elastic tendon. After the rebound phase, the leading leg enters a second phase of negative work known as the preload phase. This phase leads the way to the push-off phase, in which the elastic energy stored in the Achilles tendon is released. The push-off phase commences before and continues throughout the double-limb support phase. This phase compensates for most of the energy lost in the collision phase. Thus, collision losses have to be offset by positive work, such as push-off (see figure 6) [5].

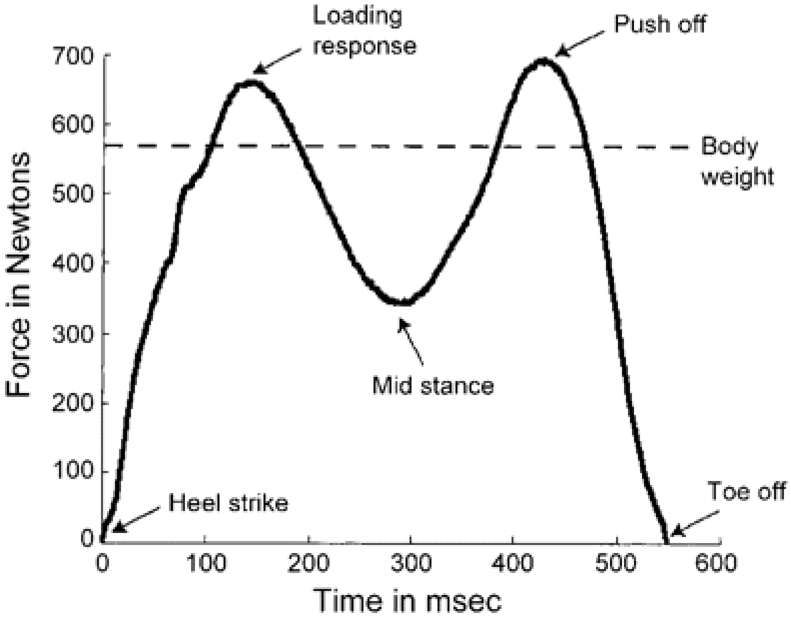

Figure 6: During gait four energetic processes subsequently take place: collision phase (0-150 ms), rebound phase (150-300 ms), preload phase (300-450 ms) and push-off phase (450-600 ms). Whereas the rebound phase and push-off phase are known to perform positive work (shifting the COM upwards), the collision and preload phases perform purely negative work on the COM (shifting it downwards) [10].

3.1.2 Metabolic costs of walking

The negative work performed to redirect the COM during human gait costs metabolic energy. This metabolic energy is often referred to as the step-to-step transition costs of human walking, in other words the costs that are made to redirect the COM during the transition between steps. These costs are largely made in the form of mechanical work performed by active muscles, such as the knees.

Essentially, humans want to minimize the metabolic costs needed for walking to save energy, and thus want to minimize the step-to-step transition costs. We have several manners to overcome large step-to-step transition costs. As mentioned before, positive work can be performed as a result of push-off and preloading to compensate for the energy dissipated in other phases. However, there are other mechanisms to reduce the metabolic costs of walking, such as actively swinging the leg back and forth, thus inducing faster leg motion. By increasing step frequency, the step-to-step transition costs could theoretically be reduced to zero. Then, the legs have to be swinged so fast that the COM is redirected almost immediately. To achieve this, one leg should contact the ground directly after the next, so that ground contact is nearly continuous and negative work is brought to an optimum of zero. However, in theory this is impossible, as humans cannot walk infinitely fast without putting in extra effort to achieve this high speed. Although the step-to-step transition costs could be brought to a mimimum when picking up the pace, the forced leg motion needed to increase walking speed would be far from costless. Humans thus want to avoid long steps in order to avoid large step-to-step transition costs (or large COM displacements), but also need to avoid fast steps in order to avoid large costs due to additional forced leg motion. Hence, changing walking speed implies a trade-off between these two avoidance mechanisms (see figure 7). At a comfortable speed, about 70 % of the net metabolic costs is due to the step-to-step transition costs, while 30% is attributable to forced leg motion [5].

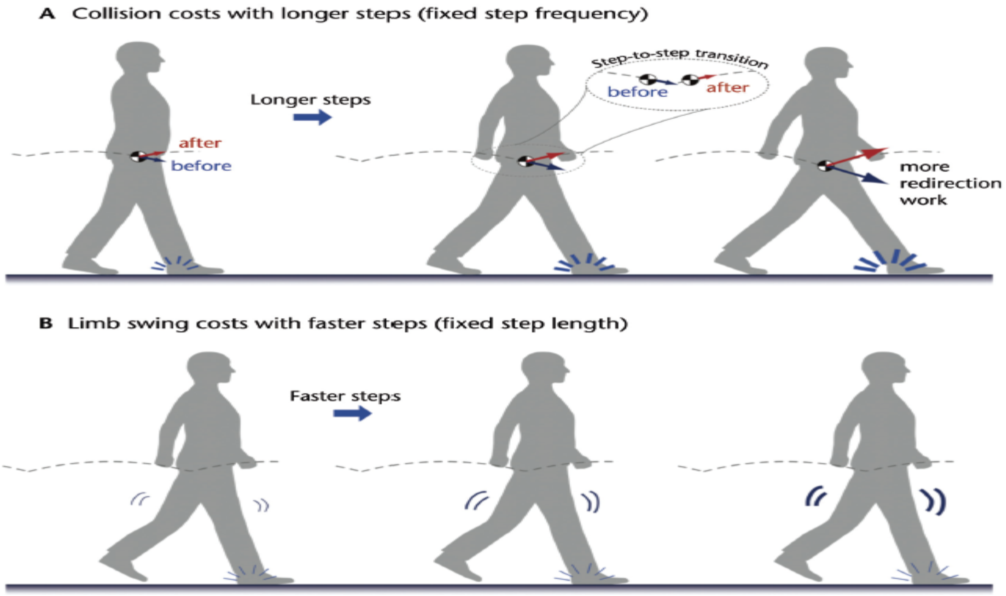

Figure 7: An important trade-off in human walking is the choice between fixed step frequency (A) and fixed step length (B). (A) Step-to-step transition costs, costs performed in order to redirect the COM, are known to increase with step length. The larger the step, the bigger the COM displacement, so the more costly it is to redirect the COM. (B) Although increasing walking speed reduces the step-to-step transition costs, it increases the costs of forced leg motion in order to reach a higher walking speed. Thus, the competition between step-to-step transition costs and forced leg motion appears to determine the preferred step length and frequency of normal human walking [5].

A more effective way for humans to reduce step-to-step transition costs is by using their feet as wheels instead of changing walking speed. Arc-shaped feet have shown to reduce negative work by reducing the directional change required of the COM (see figure 8). Ideally, the arc radius is equal to leg length so that no directional change is required, and thus no collision loss is generated. However, such feet would be tremendously impractical. Luckily, arc-shaped feet with shorted radii can still reduce collision loss, as can be seen in humans. The human foot seems to be functioning like a wheel, whereby the foot effectively rolls over the ground and the center of pressure changes position on the ground as we walk, thus effectively reducing collision losses [5].

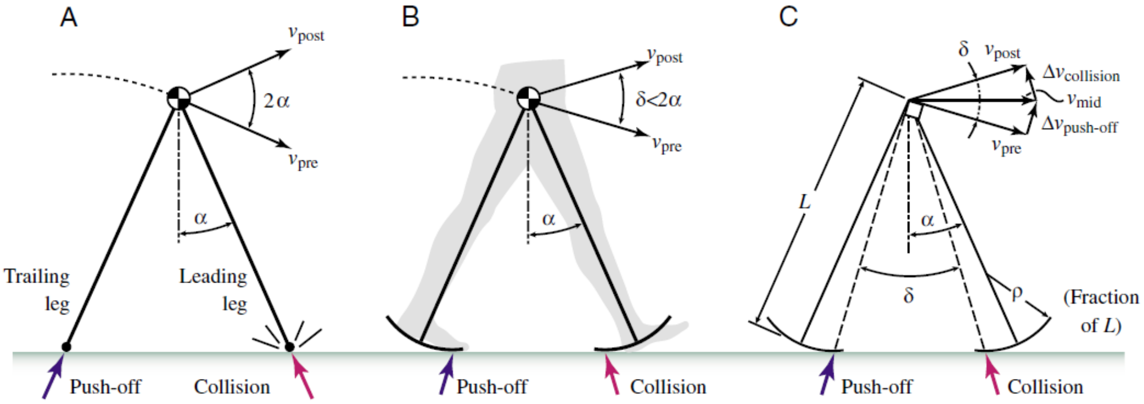

Figure 8: A simple model demonstrates the advantage of rolling feet for human beings. (A) Modelling the legs as pendulums, work is required in order to redirect the COM velocity, from pre-transition COM velocity (Vpre) to a post-transition velocity (Vpost). For these feet, the net directional change in velocity is known to be equal to the angle between the legs (2α). (B) Modelling the legs as wheels reduces the directional change in COM velocity (δ<2α) and thus the step-to-step transition costs. (C) An overview of the model. Vpre is perpendicular to the axis of the trailing leg through COM, while Vpost is perpendicular to the axis of the leading leg. Push-off by the trailing leg causes a change of velocity (Vmid = Vpre + Vpushoff). Collision of the leading leg causes a further change in velocity (Vpost = Vmid + Vcollision). The work that has to be performed is equal to the square of the velocity change (2α=δ in case of normal feet, 2α<δ in case of rolling feet) [11].

3.2 What are the general differences between robot and human walking?

Looking back on the last research question, one could say that locomotion is essentially nothing more than 'the translation of the centre of mass through space along a pathway requiring the least expenditure of energy' [12, pp. 558]. The last part showed that human beings have certain dynamic principles in order to reduce the metabolic costs of walking, such as the choice of an ideal step length and frequency, and the use of their feet as wheels. Whether the same dynamic principles count for the robot will be examined in the experiment. However, an important question that needs to be answered beforehand is: What are the general differences between robot and human walking?

3.2.1 Limitations of the robot when walking is concerned

It is unquestioned that robots have some obvious limitations in comparison to humans when walking is concerned. These limitations can roughly be divided in three groups: limitations in the way movement is generated, mechanical limitations and disadvantages due to the choice of mechanics.

The largest drawback in robot walking is the way movement is generated. In human beings movement is initiated by the neocortex of the central nervous system after which a signal is send to the second level of the motor system, namely the cerebellum and the basal ganglia, which then make important tactical decisions concerning the movement. After having decided the sequences of muscle contractions that are required to achieve a certain goal, the signal is send through to the brain stem and spinal cord. These two areas are concerned with the actual execution of the movement and make sure motor neurons become activated and muscular contraction results. Although these three levels allow movement to be executed, they do not directly allow movement to be altered along the way. One of the most important components of the sensorimotor system is the different feedback loops that have been incorporated in the system. The sensorimotor system continuously receives feedback from several other systems. Feedback from the visual system is for example needed in order to perceive changes occurring in the external environment, and sensory feedback is needed to maintain posture and muscle length [13]. In robots, movement is generated in a completely different fashion, starting from a computer signal that is send to the locomotion component of the robot. The locomotion component is then responsible for generating trajectories of the walk based on the commands from the computer and handling the joint requests through interaction with the robot. Generally, movement is generated offline (also known as open-loop), which means that the entire sequence of actions has to be planned prior to execution. In other words, there is no established feedback control like in the human sensorimotor system. Robots are thus often missing a very important part of locomotion, namely the ability to adjust movements in response to feedback from other systems and the environment. Nevertheless, there are robots that can generate their movement online, meaning that these robots can incorporate feedback while executing movement. However, this adds an extra degree of complexity to the robot and often leads to disturbances in their movement [4].

Besides this important limitation in the way movement is generated, robots have a number of mechanical limitations. First of all, robots have degrees of freedoms instead of joints. The joints that human beings have, lead to the generation of multidirectional movement, and are known to provide a relatively large range and velocity of motion. As a replacement for joints robots have degrees of freedoms, also called DOFs (see figure 9). DOFs serve the same function as joints, but have limited abilities especially in terms of the possible velocity and range of movement. DOFs can be defined as 'the number of parameters needed to specify the configuration of a mechanism, in terms of the number of links and joints and the freedom of movement allowed at each joint' [14, pp. 67]. Every degree of freedom allows for movement in a one-dimensional space, of which sliding is an example [15]. In other words, when you want to mimic a three-dimensional hip joint, you need three separate DOFs in the hip in order to allow such three-dimensional movement. The most important limitation of the presence of DOFs in robots in comparison with joints in humans is that the range of joint motion and possible joint velocities are limited for DOFs whereas they are almost unlimited for joints [16]. The exact limitation of DOFs instead of joints will be analyzed in detail in the experiment.

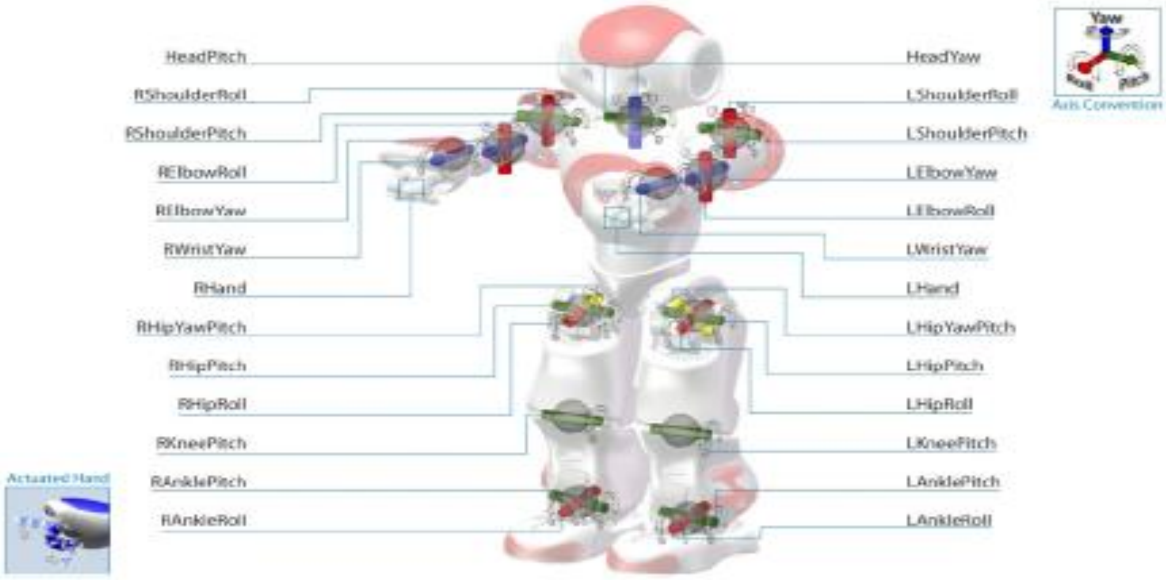

Figure 9: A picture of the Nao robot H25, which will be the subject of the experiment later in this paper. This picture sketches a clear overview of the different degrees of freedom in the Nao [4].

A second important mechanical limitation of many robots is the presence of static, non-flexible feet. While human feet are known to be quite flexible as often only the edge touches the ground, robots have rigid feet that allow it to be in close contact with the ground at all times. This is significant in relation to the dynamic stability of the robot. The robot's stability is greatly dependent on the base of support, the area of the robot that is in contact with the ground. Creating a large base of support for the robot allows the robot to achieve optimal stability while walking [3]. While having non-flexible feet is an advantage in terms of stability, it is a disadvantage in terms of walking. The large non-flexible robot feet have less resemblance with wheels than human feet, and as a consequence lead to larger step-to-step transition costs due to the reduced ability to push-off [5].

The third group of limitations are disadvantages due to the choice of mechanics. Hence, these limitations are not due to the mechanism itself, but more to the choice of the producer to employ the mechanism in a certain way. The most important limitation of robots in this group is the fact that many robots walk with bend legs. This is a well-considered choice of the producer of the robot and results from a decision based on the trade-off between generating stability and minimizing energetic requirements. Whereas bending the legs leads to a lower COM and thus minimizes the horizontal displacement of the COM (see figure 15), it is energetically very costly. Humans do not walk with bend legs, as it increases the moment of the gravitational force (a vertical force within the line of action of COM) about the knee. Consequently, it increases the amount of muscle force needed to support body weight. While this muscular disadvantage might not play a large role in robots, it certainly does constitute a large energetic disadvantage for robots to walk with bend legs [5].

3.2.2 Similarities between robot and human walking

As seen in 3.2.1, robots have important limitations in comparison to humans when walking is concerned, not only in the way movement is generated but also due to e.g. the presence of non-flexible feet that show little resemblance to wheels. However, aside from these non-human features, they have many human-like features, such as joint-like structures and a similar way in which they maintain stability during walking. Also, to a large extent the dynamic principles that humans follow can be applied to robots as well. Just like humans, robots have a gait that consists of two phases, an unstable single-limb support phase and a stable double-limb support phase. In addition, the same forces act on robots as act on humans: there is a gravitational force from the COM towards the ground and a ground reaction force equal to but opposite of the gravitational force. Furthermore, a certain price has to be paid for walking, as the step-to-step transition costs count for both humans and robots. While for humans this constitutes a metabolic cost, for robots it constitutes an energetic cost in the form of enlarged battery power needed to execute the walking movement [5].

All in all, robots have both human-like and non-human features. Whereas some dynamic principles count for both, other human principles are in shrill contrast with robot principles. Thus, there are many differences, but also many similarities when robot walking is compared to human walking. In the next part the exact differences in walking patterns and principles will be examined by looking at one robot in specific, the Nao robot.

4. Experiment

4.1 Introduction

In the above parts of this paper, literature research has been used to discover both general human dynamic principles and examine the general differences and similarities between human and robot walking. However, making a blunt comparison between humans and robots in relation to walking is not the aim of this paper. The aim is to go beyond the surface of the robotic kinesiology and discover in-depth differences between robot and human walking. The aim is to discover things that cannot be examined with the naked eye. Therefore, literature research will be combined with an actual experiment that allows for a concrete examination of the differences described before as well as a discovery of new differences between robot and human walking. With the help of Gait Analysis, a tool used to examine the walking pattern of humans, the walking pattern of the Nao Robot will be analyzed. The question that will be answered in this experiment is: To what extent does the Nao follow the same dynamic principles as humans during walking? Hypothesized is that the same dynamic principles will count for robots as do for humans. However, expected is that robots follow these principles in another fashion than humans, due to their mechanical limitations.

First, a methods subsection will elaborate on the main object of the study, the Nao Robot. It will also elaborate on the apparatus, the Gait Analysis and the motion capture program Vicon Nexus, and experimental procedure used in the study. Next, the results of the study will be analyzed. Afterwards, a conclusion will be given about the extent to which the Nao follows the same dynamic principles as humans during walking. Finally, in the discussion the findings of the experiment will be critically evaluated and the potential limitations of the study will be discussed.

4.2 Methods

In the methods section will be elaborated on the main object of the study, the Nao H25, as well as on the apparatus and experimental procedure used in the study. Also, the way the data is analyzed will be explained.

4.2.1 Subjects

The object of the experiment was the Nao Robot H25, a fully autonomous robot with 25 degrees of freedom. This robot in specific has been chosen for several reasons. The main reason was that this robot was readily available at the University of Maastricht to be used for research, as the Knowledge Engineering Faculty had four Nao robots available for academic purposes. Also, the Nao is an extremely popular robot all over the world; even the most popular robot used for academic purposes worldwide. Thirdly, the robot will be commercially available soon. Hence, it would be very interesting to examine this specific robot. And finally, the Nao Robot H25 is relatively user-friendly so that it can be used in an experiment without any problems [17].

The Nao Robot is a completely autonomous and programmable humanoid robot, developed by the French company Aldebaran. It is 58 centimetres in size and thus falls under the category of medium-sized robots. It weighs about 4.3 kilograms. However, Nao's small size and weight are compensated by the large amount of features and capabilities of the robot. The Nao can see via two digital cameras, he can react to touch via the sensors in his body, he can communicate by speaking in English or French and he can interact with other Nao's, to name a few examples [18].

As not all of these features are of huge importance for our research, the focus will lie on those features that are related especially to the kinematics of the Nao Robot. The Nao contains a locomotion component consisting of two different parts. The first part, the so called GaitEngine, receives the motion command from the computer and is accountable for generating the trajectories for the movement based on these commands. The second part, the MotionModule, receives the calculated trajectories from the GaitEngine and directly controls the degrees of freedoms to execute the movement. The Nao generates its movement by using an open-loop walk, meaning that the complete sequence of actions is planned prior to movement and large turbulences are difficult to correct [4].

Also closely related to the movement of the Nao Robot is the way balance is maintained. The Nao does this in three ways. It is equipped with an inertial central unit, composed of both accelerometer and gyrometer, to give it a sense of balance. This unit can for example send a signal to the Nao that it is lying on its back, so that it can effectively start working on getting back up. A second way balance is maintained is by the pressure sensors under the feet of the Nao. These pressure sensors allow the Nao to fine-tune its balance, by for example controlling the posture of the Nao. Balance is also maintained by simply avoiding obstacles which would lead to a collapse of the Nao. The Nao avoids obstacles with the help of two ultra-sound senders and receivers in his chest. By sending ultra-sound signals to its environment, the Nao can sense where obstacles are by interpreting the sound waves that are sent back to the robot [18].

The Nao can thus generate movement via a computer that sends signals to the locomotion component of the robot which directly interacts with the DOFs required to execute the movement. During the execution of the movement, the Nao maintains its balance with the help of the inertial central unit and the pressure sensors under his feet and avoids obstacles by sending out ultra-sound waves to surrounding objects and interpreting the feedback.

4.2.2 Gait Analysis

The Gait Analysis is a famous tool for the study of human motion. It can be used to purely measure body movement, but is also often used in the assessment, planning and treatment of individuals with walking disabilities. The last years Gait Analysis has been especially recognized as a tool in sports biomechanics, used to help athletes run more efficiently and to develop the finest possible running shoe for athletes [19].

Gait Analysis works with a passive marker system, whereby reflective markers (typically in the form of balls) are placed on anatomical landmarks of the human body, such as the condyles of the knee [19]. These markers allow for accurate recording of movement with the use of multiple cameras. These cameras send high-powered infrared strobes to the markers, after which the reflection of the markers can be recorded by matching filters in the camera. Triangulation of the markers in space is possible on the basis of a comparison of angle and time delay between the original and reflected signal. All these cameras are in connection with a computer, which is used to create 3D-trajectories from the different markers. Also, a computer model is utilized to calculate joint angles from the relative marker positions on the labelled trajectories [20].

In addition to these cameras, most movement laboratories have floor-mounted load transducers, better known as force platforms. When the patient walks over the force platform, additional things like ground reaction forces and the location of the centre of pressure can be calculated [19].

Figure 10: An overview of the movement lab, the place where Gait Analysis has been adopted of the Nao H25. The Nao walks over a 12-meter-long walkway with incorporated force platform in the middle while the movement of the markers can be recorded by the different cameras surrounding the walkway.

Gait Analysis is a non-invasive tool as the skin markers can easily be removed afterwards and no actual sensors or wires are attached to the subject. Also, Gait Analysis is a flexible method, meaning that the cameras are portable and can be moved whenever necessary. And finally, this tool is permanent, as data can be stored and used over and over again [21].

4.2.3 Experimental procedure

The Nao robot was given the motion command to walk down the 12-meter long platform in a straight line over the embedded force platform. No extra commands were given as far as velocity was concerned, so the Nao walked at a comfortable self-chosen velocity over the walkway. The Nao was tested in three different test situations: walking with both feet down the force platform, walking with the left foot down the force platform and walking with the right foot down the force platform. For each condition, five trials were collected. When the feet were not placed properly on the force platform or if the Nao did not walk in a straight line down the walkway, the trial was discarded.

The reflective markers were placed on the different degrees of freedoms of the left and right leg, on places similar to the anatomical landmarks normally used for human Gait Analysis. In total eight markers were placed on each robot leg. Fortunately, the robot did not contain any other reflective parts on its body, so no parts of the robot had to be covered up.

Figure 11abc: Sixteen different markers were placed on the different DOFs of the Nao H25.

4.2.4 Motion Capture

In order to capture the motion on screen, use was made of Vicon Nexus Software. This software ensures that the 3D-trajectories, as a result of the recorded reflection, of the different markers are sent to the computer and translated into a figure of the actual movement along with the forces working on the joints.

A wide range of different information can be calculated by Vicon Nexus, such as joint velocity, joint range, the forces and moments working on the body and the centre of pressure [22].

4.3 Results

In this section the results of the study will be brought to light. After having deducted Gait Analysis of the Nao robot H25, the data of Vicon Nexus has been put in an excel sheet after which the different parameters could be analyzed. The parameters have been analyzed by averaging out the different values of all trials. These averages have been put in different graphs that give a main overview of one or multiple parameters. Generally, the graph shows the different values of the parameter over time. However, in a number of cases it was necessary to draw a different picture, for example scatter plots or a graph with trend lines. This information can be deducted from the graphs itself per parameter.

The analysis of these parameters will serve two important functions. First, it gives important information about the way the Nao adopts a walking pattern. And second, it brings the differences between the Nao gait and the human gait forward by the information that is known already about the human gait. This way the research question of the experiment, to what extent the Nao follows the same dynamic principles as the human during walking, can be answered.

4.3.1 Basic parameters

Before going into detail about several other parameters, it is important to elaborate on a number of basic parameters of the Nao H25, such as step length and walking speed. The table that follows constitutes a clear overview of the average values of these basic parameters.

Parameter	Average value
Weight	4,3 kilograms
Size	58,0 centimetres
Step length	83,7 centimetres
Walking speed	93,9 meter/second
Time of gait cycle	840,0 milliseconds

4.3.2 Ground reaction forces

As discussed in the literature review, there are two main forces working on a body during walking. There is a gravitational force (Fgravity) acting from the centre of mass downwards and a ground reaction force (GRF) from the centre of pressure upwards. This is exactly the same for the Nao. The gravitational force should be equal but opposite to the ground reaction force at all times, as the third law of Newton describes. Every action, or force, leads to a certain reaction, another force, which is equal in magnitude, but can differ in terms of acceleration [23].

It is important to take the forces working on the Nao into account in the data analysis, because the forces are directly connected to the acceleration and consequent redirecting of the COM occurring during gait. One of the ground principles of human walking is that the COM needs to be redirected continuously by performing positive and negative work on the COM. As the robot gait is expected to show much similarity to the human gait, it is hypothesized that the same counts for the Nao.

The force platform in the experiment measures the ground reaction forces acting on the Nao. This GRF can be broken down in three components: Fx, Fy and Fz. Fz represents the vertical component of the GRF, Fy the anteroposterior component (pointing in the walking direction) and Fx the transverse component (see figure 12) [24].

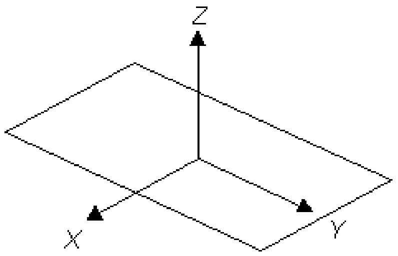

Figure 12: The ground reaction force (GRF) can be broken down in three components: a vertical component Fz, a transverse component Fx and an anteroposterior component Fy [24].

As you can see in figure 13, all of these three components are displayed over time. Fz of GRF shows a rough sinusoidal pattern pending around 45 N. This is surprising because the trend line was expected to lie around 43 N, as there is a gravitational force acting from the Nao of about 43 N. According to the second law of Newton $\boldsymbol{Fgravity = m \times a = m \times g = 4.3\,kg \times 9.98\frac{m}{s} = 42.9\,N}$ [23]. As explained above, the magnitude of the gravitational force should be equal to the magnitude of the ground reaction force, so Fz (the vertical component of GRF) should be 42.9 N as well instead of the projected 45 N. This small deviation from the expected value can be due to an offset effect.

Besides this small deviation and the general different amplitude of Fz (in humans the amplitude of the force is higher as the mass of the human body is larger), there is another large difference between the gait of the Nao and the human gait when Fz is concerned. The pattern of Fz in robots is far from the pattern that is expected when looked at human beings (see figure 6 and 14). While humans show a great amount of constancy in their Fz during gait, the Nao has a very inconsequent pattern of Fz. It seems like the robot continuously has to compensate for disturbances and hence, is unable to create a smooth force pattern. The fact that the Nao suffers more from issues of instability and is more prone to disturbances than humans might serve as an explanation for this differential pattern.

Fx and Fy of the Nao, on the other hand, show a relatively smooth sinus-like pattern (see figure 13). This pattern of Fx and Fy is similar for humans as for robots, as is shown in figure 14, although the amplitude of both forces is again significantly lower than seen in human beings. It is different from the Fz line because Fx and Fy are taking both positive and negative values and thus represent the positive and negative phases of acceleration during gait. This sinus pattern results from the redirecting of the COM. When the COM has to be redirected upwards, a positive acceleration takes place and the GRF becomes larger than the gravitational force, whereby Fx ends up in a value above 0. In case the COM has to be redirected back downwards, a negative acceleration/deceleration takes place and the GRF drops to a value smaller than the gravitational force, represented by a value of Fx below 0. Fy shows the exact opposite sinus pattern. Although the pattern per se of Fx and Fy of the Nao is fairly similar to the human patterns of Fx and Fy, the pattern seems to show extra periods of positive and negative acceleration. In the first half of the gait, during a period of positive acceleration, there is an additional period of negative acceleration taking place (from 0,26 s to 0,34 s). Also, in the second half of the gait, during a period of negative acceleration, there is an extra period of positive acceleration taking place (from 0,70 s to 0,78 s). This is another proof for the hypothesis that the Nao is more prone to disturbances and continuously has to correct its own pattern.

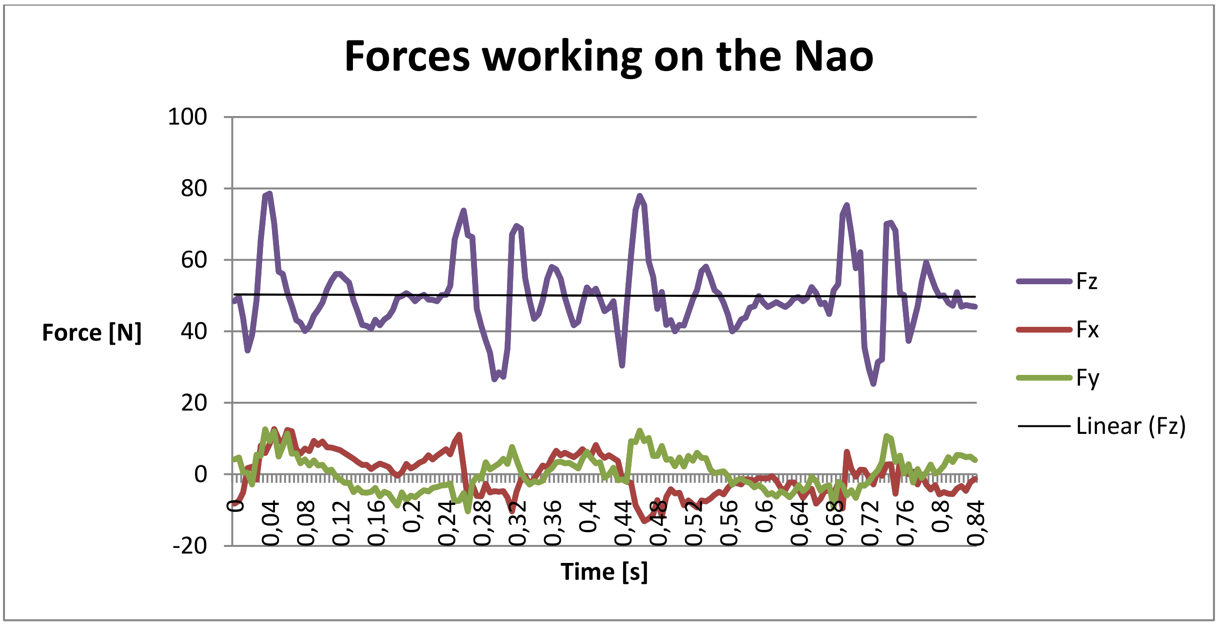

Figure 13: An overview of the ground reaction forces working on the Nao H25 during one gait.

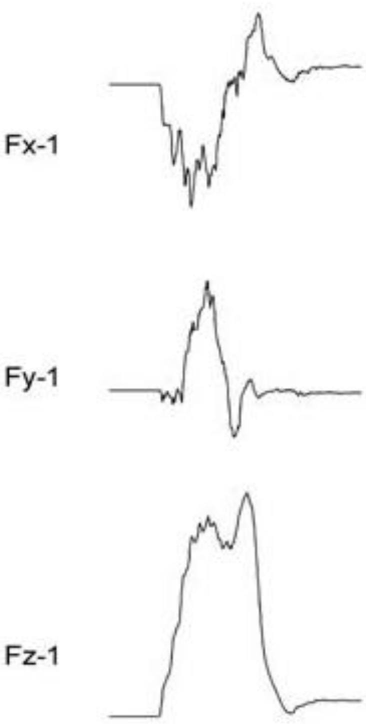

Figure 14: A human example of the Fx, Fy and Fz of the GRF during gait. Fx and Fy both show an opposite sinusoidal pattern, while Fz shows a completely different pattern with two major peaks [25].

4.3.3 COM position

The COM position is that point of the body where the mass is said to be concentrated. From it, a gravitational force acts downwards. Information about the COM position is extremely valuable, as the position of the COM is closely connected to issues of stability. The COM should remain relatively stable in both the anteroposterior and transverse direction in order to prevent falling forwards or side wards.

The COM position can be divided in three components: COM z, COM x and COM y. Whereas COM x and COM y represent the COM position in a two-dimensional field, COM z represents the COM position in a three-dimensional way by giving information about the height of the COM in the body. COM x, on the other hand, gives information about the COM position in the transverse field and COM y says something about the COM position in the anteroposterior field.

As you can see in figure 16, COM z shows a straight line over time at about 280 millimetres. In other words, the height of the COM stays constant at 28 centimetres from the ground the entire time. As described in 4.3.1 the total height of the Nao is 58 centimetres, so the COM is positioned at about 48% from the total height. This percentage is significantly lower than witnessed in humans, whereby the COM is generally positioned at about 56% of the total height of the body. Thus, the COM z for the Nao is placed lower in the body, something that has probably been established intentionally, as it is easier to maintain stability with a lower COM (see figure 15) [26].

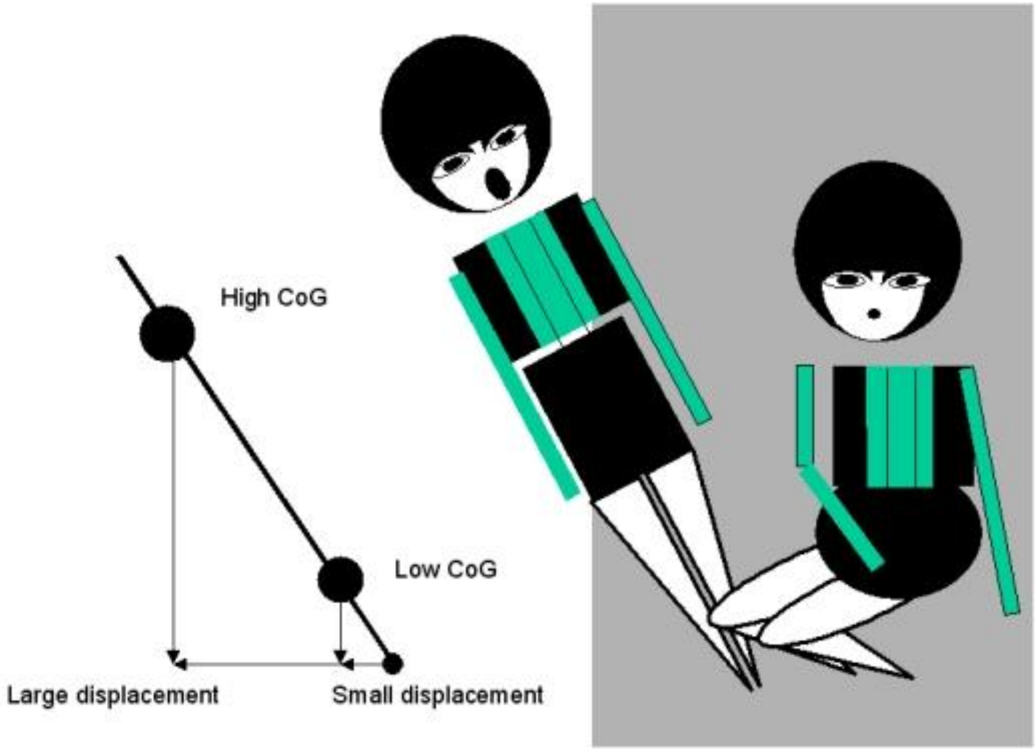

Figure 15: A low COG or COM increases the stability of an object, as a disturbance leads to a small displacement of the COM from the base of support. A high COG or COM, on the other hands, leads to large displacements from the base of support when disturbed, thus leading to issues of instability [26].

Another important difference in relation to the vertical displacement of the COM in case of the Nao is that the COM z stays almost constant over time (see figure 16). The producers of the Nao H25 have decided to minimize the vertical displacement of the COM, probably in order to avoid continual redirecting of the COM. The vertical COM in human beings, however, remains a certain displacement over time as and can be represented by a sinus-like pattern as described in figure 2.

COM y, the horizontal position of the COM over time, shows the expected pattern in the sense that it increases over time (see figure 16). As the Nao is moving in this anteroposterior direction during the experiment, it is logical that the positive value of the y component of COM increases over time.

COM x, however, shows a completely different pattern, namely a consequent sinusoidal shape over time (see figure 16). This is due to the fact that the COM displaces from step to step in the transverse field. During a single-limb support phase whereby the left leg supports the body, the COM will shift to this leg. On the other hand, during a single-limb support phase whereby the right leg supports the body, the COM will shift to the right leg. Hence, the COM does not remain at the same position in the transverse plane, as it moves from leg to leg during one gait. This explains the sinusoidal pattern of COM x.

The sinusoidal pattern takes a small bend downwards over time, as the Nao robot did not move in a completely straight line, but tended to move towards the right after about 1.5 seconds.

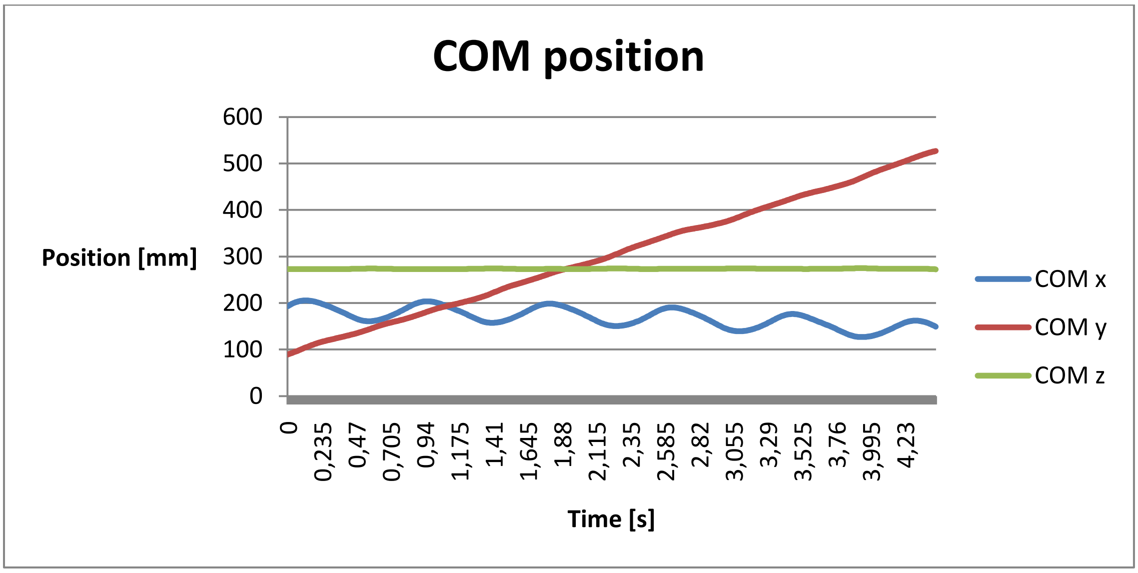

Figure 16: Graph showing the displacement of the COM over time. COM z represents the height of the COM, COM x the transverse displacement of the COM and COM y the anteroposterior displacement of the COM.

As COM x, the displacement of the COM in the transverse direction, shows a consequent sinusoidal pattern, COM y has to be displayed as a straight line (see figure 16). Despite the transverse displacement of the COM, the anteroposterior displacement shows a straight line as the displacement in the anteroposterior plane is constant every time period. This can be seen in figure 17 below, whereby the anteroposterior displacement of the COM is about 80 mm for every sinus pattern displayed. If the anteroposterior displacement is constant over time, COM y has to be a straight line as it shows a linear increase.

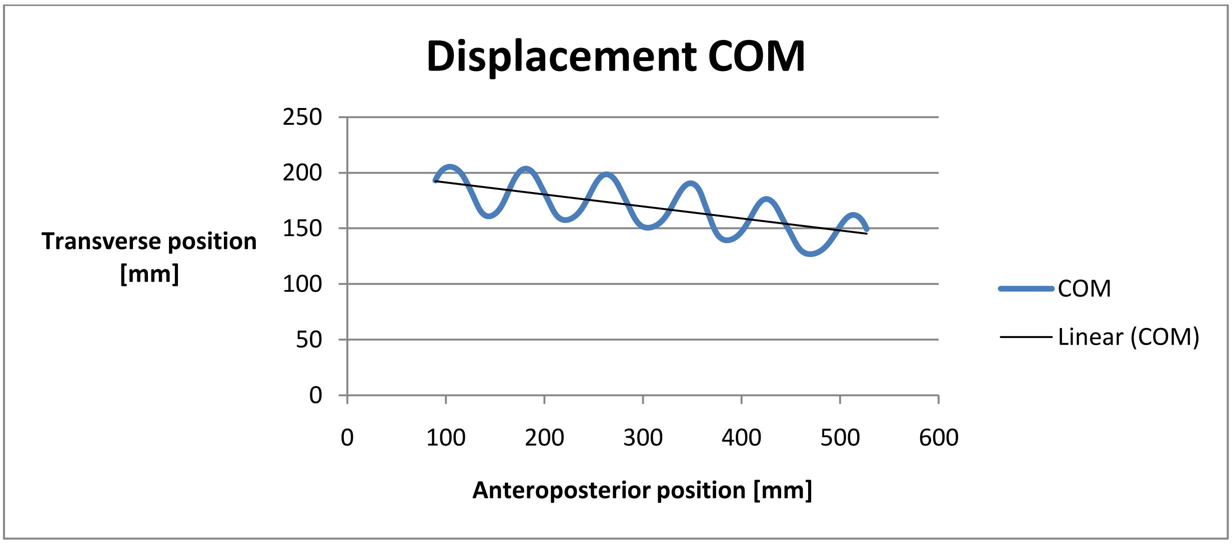

Figure 17: A scatter plot shows the actual displacement of the COM in both the anteroposterior and transverse planes over time. The trend line shows the estimated movement pattern of the Nao.

4.3.4 COP position

The centre of pressure (COP) is the point on the ground from which the ground reaction force acts in response to the gravitational force acting downwards. The centre of pressure is valuable to measure as it says something about the point from where the GRF acts, leading to a certain moment around that point, which can influence the walking pattern of the Nao.

The COP position of the Nao has been calculated in a similar manner as the COM position, with both an anteroposterior (COP y) and a transverse (COP x) component. There is no COP z as the COP is always positioned at a point on the ground so it does not have any height and the COP z would show a line equal to zero.

COP x, the transverse position of the centre of pressure, shows a relatively large displacement over time (see figure 18). Just like the COM, the COP changes position on the transverse plane during walking. Whereas the COP should be at the left foot when the left leg supports the body during single stance, the COP should be at the right foot when the right leg supports the body during single stance. However, because the COP also moves around the foot itself during one single stance phase, COP x has not such a clear sinusoidal pattern as COM x.

COP y, the anteroposterior position of the centre of pressure, shows a positive line just like COM y did (see figure 18). The reason for this is the same as explained before. Because the Nao moves in an anteroposterior direction, the anteroposterior value has to increase over time. However, in contrast to the straight line of COM y, COP y shows a rough sinus-like pattern. Because the COP moves a lot in the anteroposterior plane sometimes, but hardly changes in this plane at other times, the COP y shows a sinus-like pattern. The roughness is due to the fact that COP x shows an inconsequent pattern, so that the anteroposterior displacement of COP is not constant per time period.

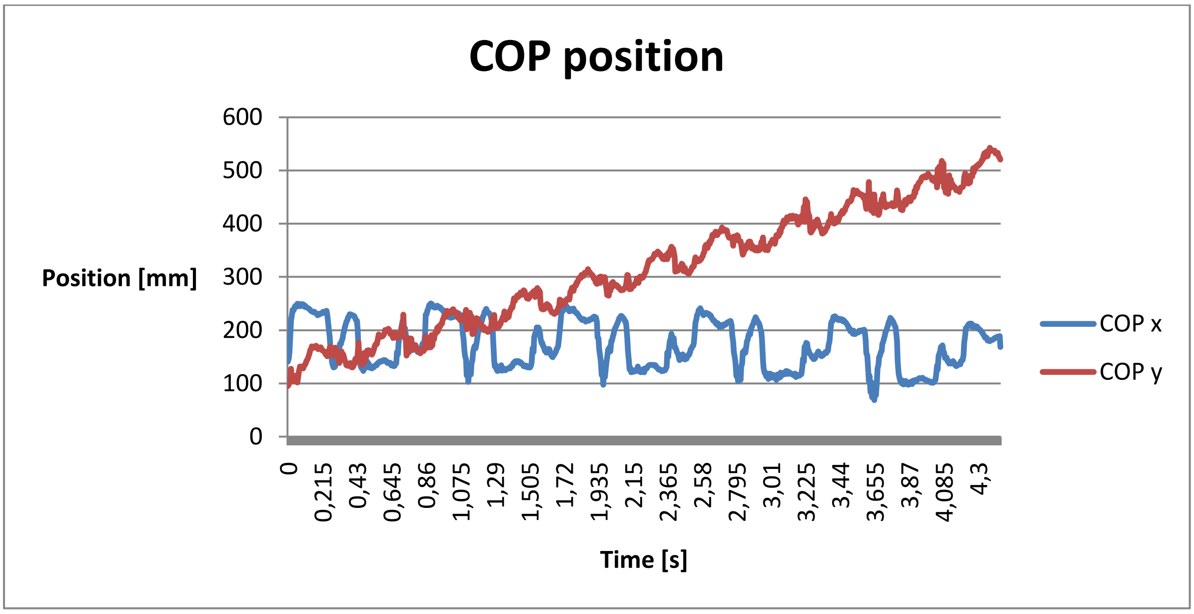

Figure 18: Graph showing the anteroposterior and transverse displacement of the centre of pressure over time.

The actual displacement of the COP in the anteroposterior and transverse planes has been displayed in figure 19 and 20. As can be seen clearly in figure 20, the COP does not only move from foot to foot during one gait, but also switches position on the foot itself during the single stance phase. The first peak in figure 20 shows a left single-limb support phase, whereby the COP moves anterior during the phase itself. Once the right foot touches the ground, the COP moves to the right foot. However, the COP moves back to the left foot when it pushes off from the ground in order to displace the COM at the end of the double-limb support phase. During the right single-limb support phase, the COP moves back to the right foot and remains on the right during this phase, although it does move anterior over time.

Given the fact that the Nao robot has non-flexible feet, it is interesting that the displacement of the COP during one gait still shows a lot of resemblance with the COP displacement in humans. It seems like, despite the inflexibility of its feet, the Nao can still move the COP anterior during a single-limb support phase. This might be due to the flexibility in the degree of freedom in the ankle of the Nao, which can direct the COP forwards during gait.

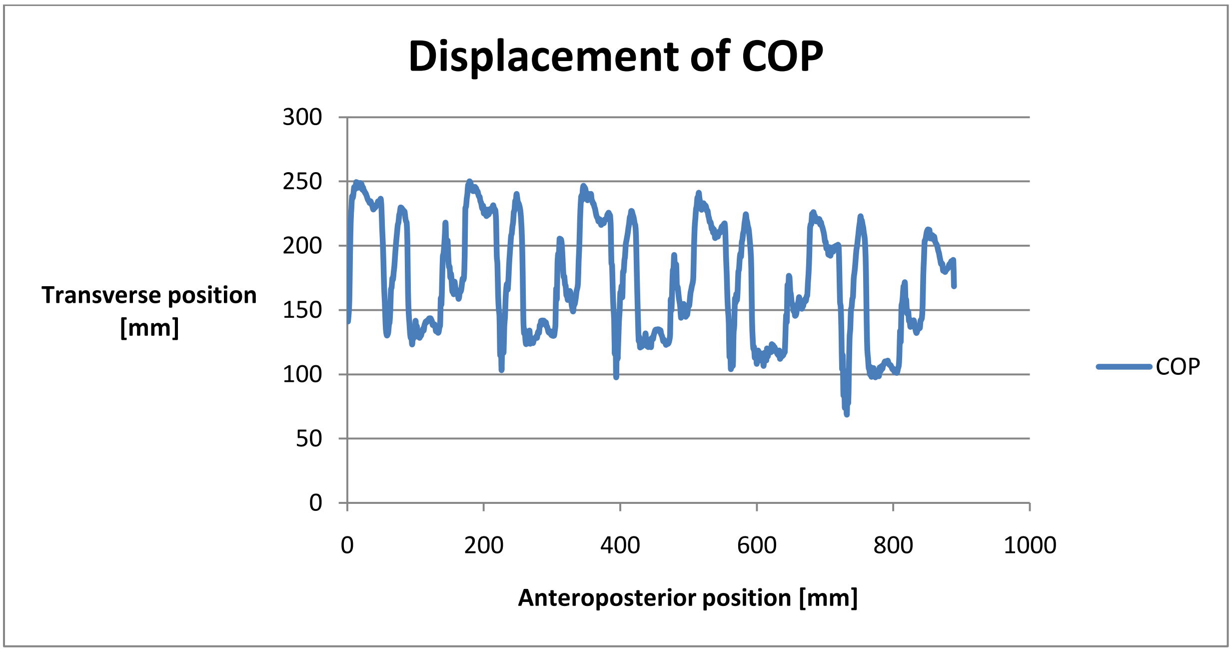

Figure 19: The actual displacement of the centre of pressure.

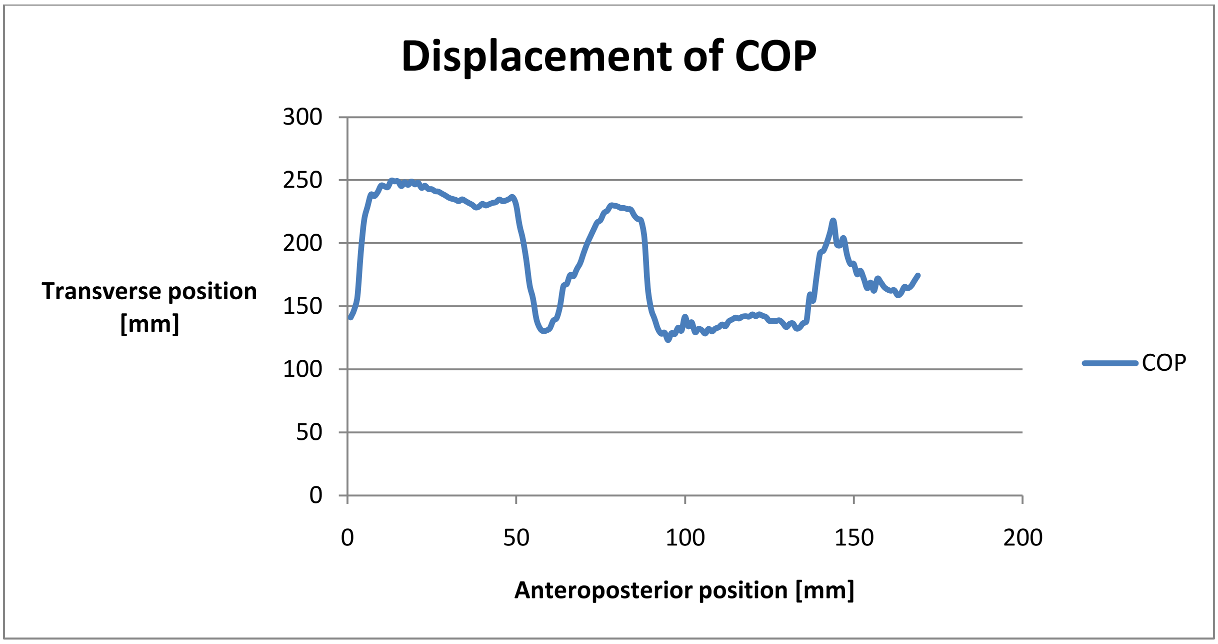

Figure 20: The actual displacement of the centre of pressure during one gait.

4.3.5 COP in relation to COM

Not only is the position of the COM and COP itself important while analyzing the data of the experiment, the relationship between the COM and the COP, specifically the distance of the COP from the COM, is just as important. As there is a ground reaction force acting from the COP upwards, movement around the COM can be caused. The further apart the COP is from the COM, the easier this disturbing movement around the line of gravity is caused. However, when the COP is close to the COM, it is relatively hard to cause disturbances around the line of gravity. The distance of the COP from the COM thus constitutes a driving force. This driving force is often called the centre of mass acceleration, and is directly proportional to the distance between COP and COM. Generally, the centre of mass acceleration is larger in elderly individuals and people with neurological impairments, thus showing that a high centre of mass acceleration is certainly not a good thing [27].

The relation between COP and COM has been examined in both the anteroposterior and transverse planes. In the anteroposterior plane, it can be seen that the COM falls within the COP the entire time (see figure 21). Whereas the COM shows a straight positive line, the COP shows a rough sinusoidal positive pattern due to the transverse and anteroposterior displacements during gait.

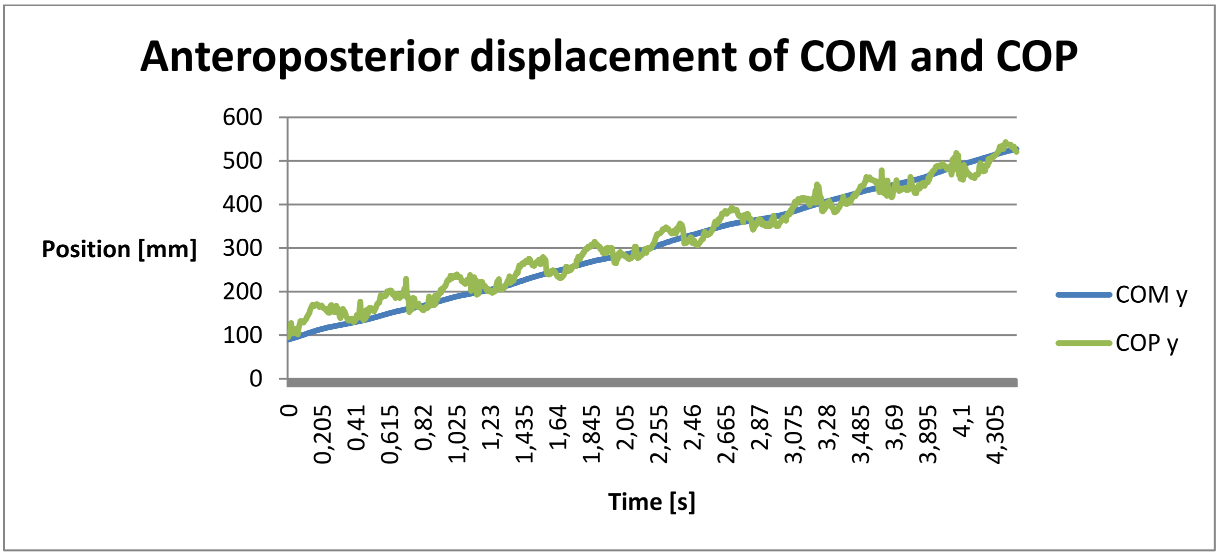

Figure 21: The anteroposterior displacement of both the COM and the COP in one graph.

Also in the transverse plane COM falls within COP the entire time (see figure 22). Both the COM and the COP show transverse displacement, although the COP shows a relatively larger displacement than the COM. Whereas the transverse displacement of the COM shows a striking sinusoidal pattern, COP x shows somewhat more of a rougher pattern due to the additional anteroposterior displacement of the COP during single-limb support phases. The downwards line is due to the Nao's deviation in direction during walking.

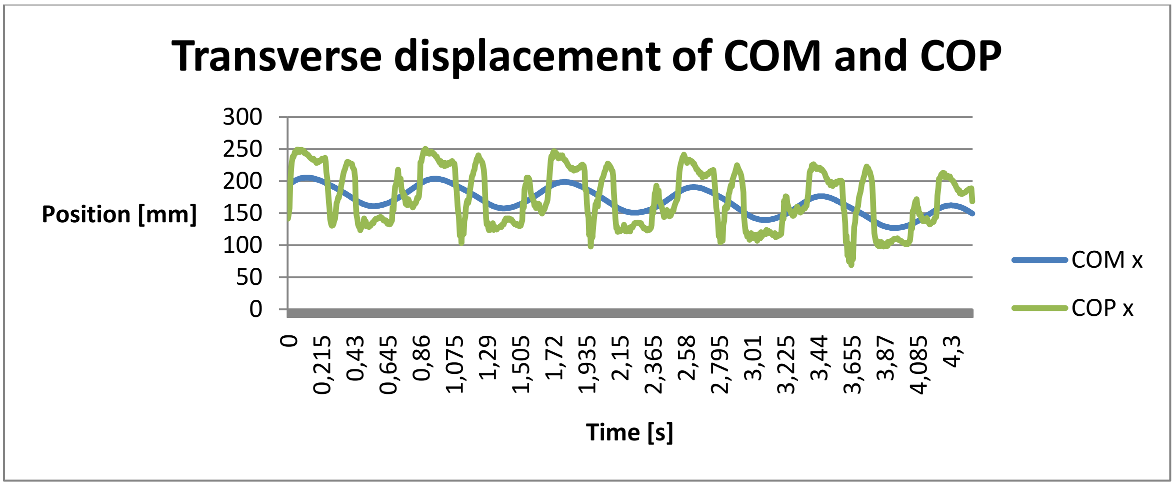

Figure 22: The transverse displacement of the COM and COP in one graph.

The fact that the COM falls within the COP in both the anteroposterior and transverse planes constitutes another similarity between the Nao and the human gait. However, what is more interesting is the exact difference between COP and COM, in other words the acceleration of the centre of mass. From figure 23 the centre of mass acceleration can be calculated. The difference COP – COG in the Nao H25 ranges from 15 to 100 millimetres. In comparison, COP-COG in humans ranges from 7,5 to 12 mm for young individuals and 12,5 to 20 mm for elderly [27]. Thus, the acceleration of the centre of mass is significantly larger for the Nao than for the human. This is expected to be due to the different control strategy of the Nao during gait. Whereas human beings continuously incorporate sensory feedback during walking, the Nao only does this at certain fixed time moments leading to occasional moments of large adjustments in response to feedback. To accompany these large responses, the Nao needs a higher gain controller system that generates a large response to a certain amount of disturbance. This can result in cases of overreaction, which result in exceptionally large accelerations of the centre of mass [28].

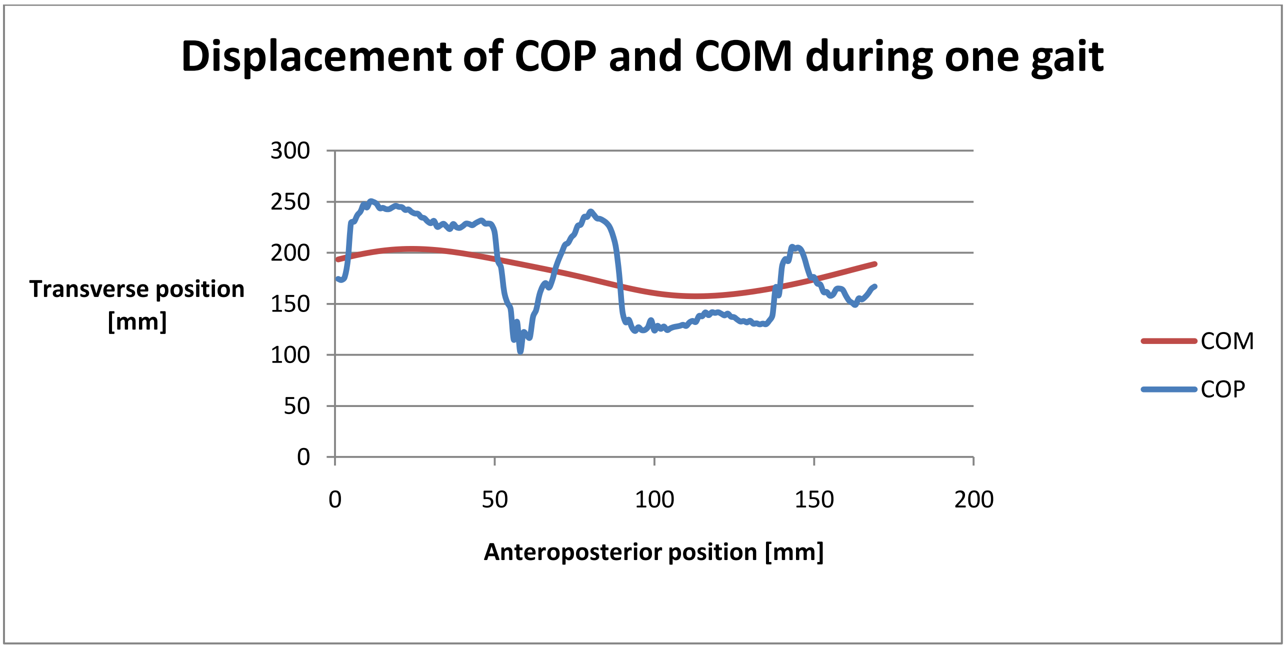

Figure 23: The actual displacement of COP and COM in the anteroposterior and transverse planes. From this graph the acceleration of the centre of mass can be calculated.

4.3.6 Base of support

The base of support of the Nao H25 is that part of the Nao that is in contact with the ground during double stance. It can roughly be seen as the surface of both feet of the Nao and the ground in between both feet. The base of support of the Nao is relatively large due to the large size of his feet. The size of the Nao's feet is 15,5 cm in length and 8,5 cm in width, creating a total size of base of support of 20 by 15,5 centimetres (see figure 24).

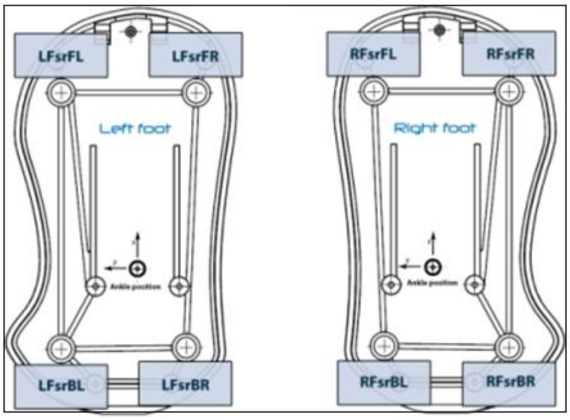

Figure 24: The base of support of the Nao: 20 centimetres long and 15,5 centimetres wide.

The Nao needs such a large base of support because it gives stability to the body of the Nao. The larger the base of support, the easier it is to maintain stability during walking, as a disturbance leads to a smaller displacement of the COM from the large base of support. However, generally counts that the larger the base of support, the smaller the flexibility of the robot as it becomes harder to move smoothly with large feet. The size of the base of support thus constitutes a trade-off between flexibility and stability. In the case of Nao, stability is of greatest importance so a large base of support has been chosen. . However, as seen in 4.3.3 the loss in flexibility of the Nao is limited (as anteroposterior movement of the COP during gait is still possible due to the flexible ankle).

The human has an evenly large base of support because stability needs to be ensured. However, humans achieve great flexibility at the same time by their presence of flexible feet. So, where the Nao needs to make a certain trade-off between flexibility and stability, humans achieve the best of both worlds.

4.3.7 Range of joint motion

One of the limitations that has already been discussed before is the limited range of joint motion for robots to the features of DOFs. DOFs have, unlike human joints, boundaries when it comes to the range of joint motion that can be achieved. The exact range of joint motion of the hip, knee and ankle have been tested during the experiment by examining the angle they can achieve. The angles have been defined as the angle difference between the vectors of the two segments surrounding the joint. As an example, the angle of the hip is the angle between the vectors of the trunk and thigh. All angles have been examined during flexion only.

Figure 25 shows that the range of joint motion for the Nao is indeed limited in comparison to human beings. The average range of the hip is about 24 degrees, the average range of the knee 19 degrees and the average range of the ankle 29 degrees, as calculated from figure 25. In contrast, the average range of hip motion in humans is 120 degrees, the average range of knee motion 135 and the average range of ankle motion 50 [29].

Another striking element in figure 25 is that all joints in the leg seem to move at the same time, while in humans this happens in proximodistal order, starting with the movement of the hip and ending with the movement of the ankle. The synchronous movement of all joints in the Nao makes sense as all joints are stimulated at the same time by the MotionModule after having received a trajectory from the GaitEngine (see 4.2.1).

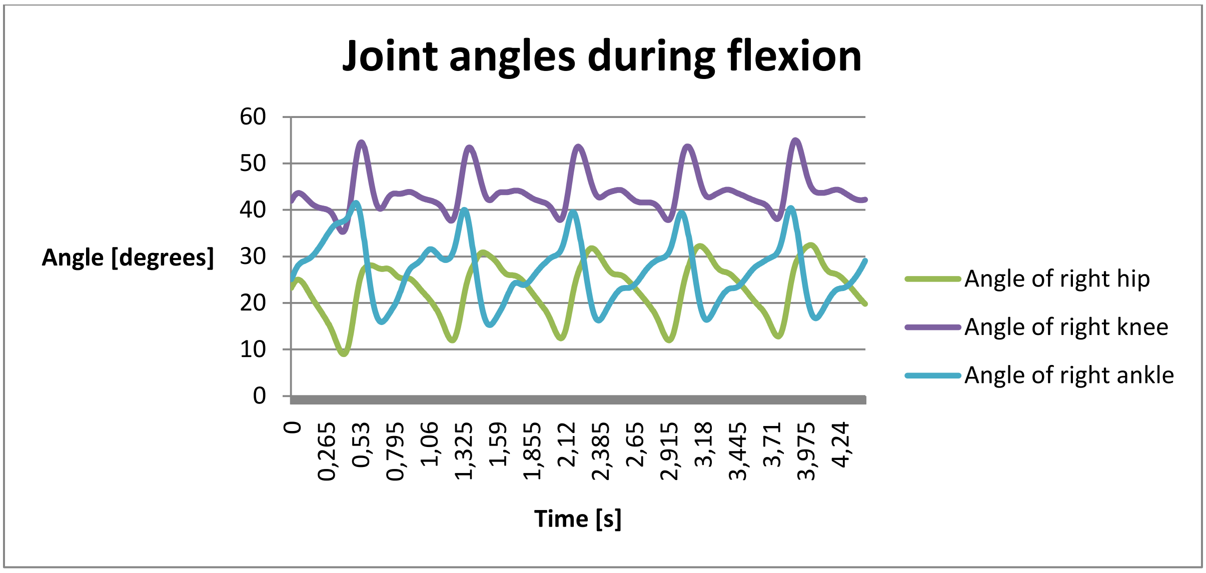

Figure 25: The joint angles of the hip, knee and ankle during flexion.

4.3.8 Summary of the results

With the help of Gait Analysis an experiment has been conducted with the Nao in which the question was answered: To what extent does the Nao follow the same dynamic principles as humans during walking? This question has been investigated by looking at seven different components that are very characteristic of gait.

Concerning the forces that act on the Nao, the Fz, or vertical component of the GRF, shows a strikingly different pattern than the Fz seen in humans. In the Nao's Fz no clear pattern can be distinguished, while humans show great consistency in a certain pattern and repeat this pattern over and over again. The inconsistency of the Nao is probably due to the fact that the Nao has to compensate for disturbances continuously and is therefore unable to create a smooth force pattern.

The second component of the gait that has been examined in the experiment is the position of the COM. Vertically, the COM of the Nao lay much lower when compared to human beings. This lowered COM has positive consequences, in the sense that it ensures stability. The lower the COM, the smaller the displacement of the COM from the base of support during disturbances. Another striking difference between the Nao and the human is that the COM of the Nao remains at a constant position in the vertical plane, while the human is famous for showing a sinusoidal pattern of vertical displacement of the COM.

Not only the position of the COM has been examined, but also the COP position has been investigated. The transverse and anteroposterior component of the COP show a fairly similar pattern for the Nao and for the human. However, the pattern of the Nao is somewhat more irregular. This might be directly connected to the fact that the Nao is more prone to disturbances than the human being is.

The next element that has been reviewed is the difference between the COP position and the COM position. This difference is characterized as the acceleration of the COM and can also be seen as a driving force. The Nao shows a significantly larger difference in COP-COM position than the human does, and consequently has a larger acceleration of the COM. This can possibly be due to the different control strategy of the Nao that is likely to result in overreactions.

Besides this larger acceleration of the COM, the Nao also has a notably larger base of support as the feet of the Nao are relatively large in comparison to humans of the same size. This large base of support guarantees stability to a large extent. As described before, a large base of support leads to a smaller deviation of the COM from the base of support during disturbances, and thus leads to more stability.

The last component of the Nao's gait that has been examined is the range of joint motion in the leg. The Nao has a considerably smaller range of joint motion in the hip, knee and ankle than the human. This is a result of the presence of degrees of freedoms in robots, while humans have joints that have large range of joint motions. Another aspect that stood out was the synchronized functioning of all joints in the Nao during flexion, whereby the hip moved at exactly the same time as the ankle did. Humans, in contrast, move their joints in proximodistal order, as they are able to control every joint individually.

4.4 Discussion of the experiment

The experiment brings to light a number of interesting differences between the gait of the Nao H25 and the human gait, which could not have been unveiled without Gait Analysis. Some differences are highly surprising, such as the fact that the centre of mass of the Nao remains at a constant vertical position the entire time. Other differences, such as the limited range of joint motion in the Nao, were expected before conducting the experiment. The implications of these findings are large, as the experiment contains vital information about the gait of the Nao and can serve as valuable feedback for the future development of robots.

The experiment contains constructive feedback about the issues of stability and flexibility. A number of important causes of instability have been brought forward, such as the large acceleration of the centre of mass and the inconsistency of Fz of GRF. By aiming on a smaller difference between the COG and COM positions and more consistency in Fz, the robot will be able to achieve larger stability in the future. Concerning flexibility the Nao also has some plausible limitations, such as the limited range of joint motion due to the presence of degrees of freedoms. Overcoming this problem will be more difficult as an alternative to the degrees of freedoms that are currently being used is still unavailable. Hence, by looking carefully at the results of this experiment important conclusions can be drawn about the gait of the Nao H25. These conclusions are extremely beneficial for the future development of robotics.

All results of the experiment are significant and accurate. Nevertheless, the experiment has a number of weaknesses. Because Gait Analysis has never been used to analyze the walking pattern of robots before, the placing of the markers was relatively complicated as there were no known landmarks on which the markers could be placed. Instead, the markers were placed on and around the degrees of freedom of the Nao in the hope that this would work for Gait Analysis. For a number of markers Vicon Nexus showed a significant adaptation in the angle between the two vectors formed by three selective markers. This helped in determining whether the markers were placed significantly on the joint. In case of proper placement of markers, one vector should be pointing in the walking direction and the other vector through the axis of the joint. When this was not the case and the angle between the vectors was different from 90 degrees, one could conclude that the markers were not placed properly on the joints. For these cases, the places of the markers have been manipulated manually in Vicon Nexus until the angle between the vectors became as close to 90 degrees as possible. Hence, the confounding influence of the placement of markers on the results has been minimized. However, this might still count as a potential limitation of the experiment. Another drawback of the experiment is that reflective markers were only placed on the lower body of the robot. Although this gives a satisfactory general picture of the walking pattern of the Nao and an accurate measurement of the joint velocities, the COG and COM positions are more difficult to determine when there are no markers placed on the upper body. A third limitation of this experiment might be the fact that relatively few trials have been done: only five trials per condition have been recorded. Hence, the external validity of the experiment might be questioned. Finally, a last potential limitation of this experiment is the Gait Analysis itself. As this program is developed to be used for human beings and animals and has never been tested on robots, the accuracy and validity of the program might be less for humanoid robots but no exact data about this are available yet.

5. Conclusion

The problem statement that stood central in this paper was: To what extent can the robot gait be compared to the human gait? This problem statement has been examined by a combination of literature and experimental research.

In the literature review has been explained what the human gait actually is and which dynamic principles count for human walking. A number of dynamic principles have come to light, such as the different phases the human gait consists of: two single-limb support phases and two double-limb support phases. Another important principle that counts for human walking is the fact the ground reaction forces acting on the body are always equal in magnitude, but opposite in direction to the gravitational force acting from the body. A third vital component of human gait is that humans continuously redirect their centre of mass during walking by performing positive and negative work on this point. This results in a sinusoidal pattern of the vertical displacement of the COM over time

In the second part of the literature review has been analyzed what general differences exist between robot and human walking. Robots have a number of limitations when walking is concerned. Their main limitation lies in the way movement is generated and feedback is incorporated into the system. Besides practical differences, robots also have striking mechanical differences in comparison to humans, such as the presence of degrees of freedom instead of joints and the presence of non-flexible feet. Furthermore, robots have limitations due to the choice of mechanics. The most important limitation in this group is the fact that the robot walks with bend legs. Despite all these non-human features, robots also have a number of human-like features. They have a similar way to maintain stability as humans, the same forces act on robots as do on human beings during walking and their phases during gait are similar to the phases recognized in humans.

After having examined some general differences between robots and humans and having looked closely at a number of dynamic principles, Gait Analysis has aided in answering the question to what extent the Nao follows the same dynamic principles as the human during walking.

A number of differences stood out when examining the gait of the Nao: the inconsistent pattern of Fz, the lowered position of the COM, the constant vertical position of the COM, the large acceleration of the COM, the large base of support and the limited range of joint motion of the hip, knee and ankle. Although a large number of features were similar for the Nao as for the human, these differences show that the gait of the Nao is by far not identical to the human gait.

Two of these appear to be a consequence of the intentions of the producers of the Nao, namely the lowered position of the COM and the large base of support. A stable equilibrium can be reached by having a low position of the centre of mass, but also by having a large base of support. By employing both, the Nao achieves almost guaranteed equilibrium. Taking into account the limitations of the Nao, specifically about the incorporation of feedback in the system, this is a smart move from the makers of the Nao. As the Nao cannot continuously respond to feedback from the direct environment and react to disturbances immediately, it is useful to develop the Nao in such a way that maximum stability is achieved during stance.

The other differences unveil the problems that the Nao runs into while walking. Especially the inconsistent pattern of Fz and the large acceleration of the COM present the inherent limitations of the Nao in terms of walking. In comparison to humans, the Nao is extremely prone to disturbances.

This susceptibility to disturbances has two important consequences for the gait of the Nao, which have been brought to light in the experiment. First of all, the Nao is unable to create a smooth force pattern while walking. And secondly, the Nao has to compensate for these disturbances continuously to avoid serious issues, such as falling over.

All in all, the robot gait can be compared fairly well to the human gait as the same dynamic principles generally count for robot walking as for human walking, such as the principle that the ground reaction forces acting on the body are always equal in magnitude, but opposite in direction to the gravitational force acting from the body. However, the manner in which the robot acts upon these principles has been shown to be different from the way the human follows these principles, e.g. by keeping the COM vertically constant instead of redirecting the COM continuously. While their final destination (adopting a walk) is identical, robots choose to follow another road to get to this destination. The choice for this different road is partly due to the decisions of the producers of the Nao, and is partly a consequence of the inherent limitations of the Nao.

6. Discussion

While many studies have analyzed robot motion from a mathematical perspective, this study has taken a kinesiologic perspective and has analyzed robot motion with the help of Gait Analysis. Instead of discovering obvious differences between the robot and human gait, less visible differences have been brought to light in this study. These differences are much more valuable as they contain information about the origin of the problem, and do not just examine the problem itself.

The implications of the result of this study are large, as it serves as important feedback for the future development of robotics. The experiments showed that the Nao has several limitations when walking is concerned. Although some of these limitations are inevitable, such as the fact that it is more prone to disturbances in general, a number of limitations can be overcome in the future. Ideally, the Nao should incorporate feedback during walking the entire time, so that overreacting can be avoided and continuous adjustment to disturbances can take place. This can limit the overall effect of disturbances. Also, the stability of the Nao can be improved, by minimizing the transverse displacement of the COM during walking as well as the acceleration of the COM, for example by placing the COP closer to the COM. Finally, the flexibility of the Nao can be improved. One way to do this is by enhancing the range of joint motion of the DOFs.

Future research should try to implement the ideas brought forward in this study in the Nao H25 or a next version of the Nao. Ideally, it combines the discovered limitations of the Nao with mathematical algorithms that serve to overcome these limitations and improve the actual quality of walking. It would also be interesting to look more in detail at the issue of stability, as this has only been examined roughly in this study. By combining Gait Analysis with tools to examine stability during walking, interesting conclusions about the stability of the robot in specific can possibly be drawn. Finally, it would be interesting to examine multiple robots with the help of Gait Analysis to see whether the strengths and limitations of different robots can be combined in the future.

7. References

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