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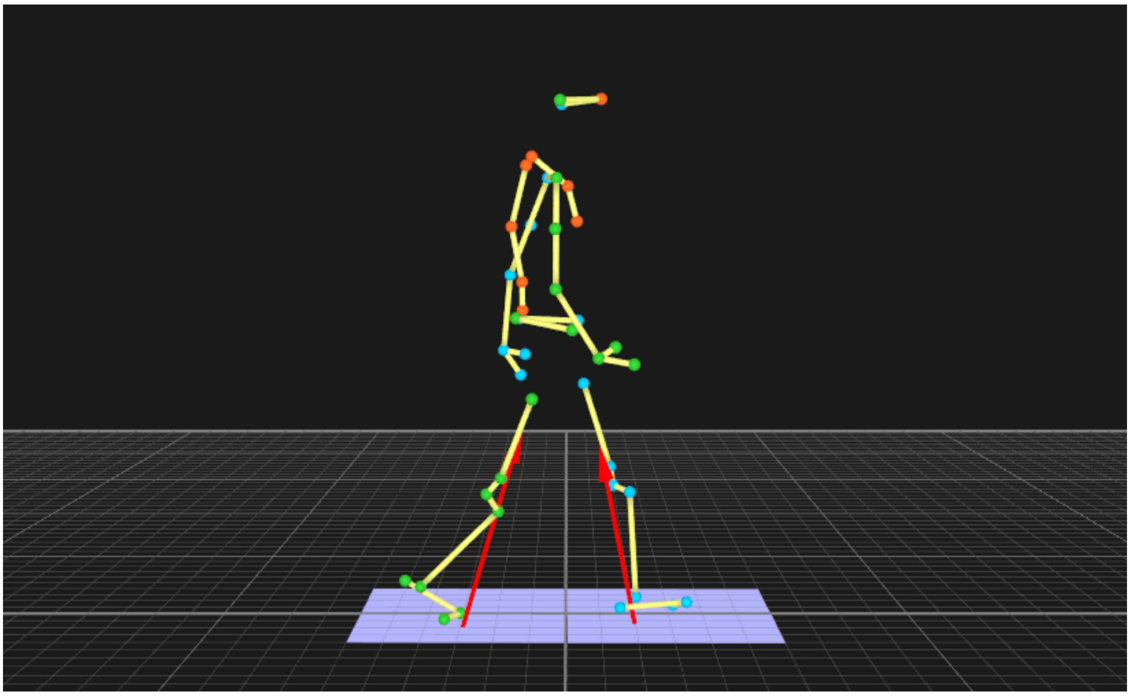

An investigation of two different skin marker models for 3D gait analysis of the trunk

A comparative analysis of a trunk model from Instituti Ortopedici Rizzoli and the Lundberg skin marker model

Master's thesis in Biomedical Engineering

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Cover: The IOR full body skin marker model as seen in Qualisys Track Manager.

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Abstract

Introduction: Three dimensional (3D) gait analysis is used clinically for diagnostics as well as in pre and post operative measurements for patients with gait disorders, and the ability to achieve reliable data is therefore of great interest. Different marker models for trunk tracking has been developed over time, utilizing a rigid-body approximation or multiple segments for modeling the trunk in more detail. Approximating the trunk as a single segment might have some drawbacks, but could be more efficient. This report aims to compare two different models for trunk-tracking, one with a single trunk segment and the other with a thorax segment.
Methods: 3D gait analysis was done on 33 healthy subjects using a full-body, hybrid marker model made of two established skin marker models. The subjects where measured while walking, and data from the pelvis and the trunk, as well as temporospatial parameters, were analysed further.
Results: The results shows close similarities between the models considering the pelvis segments and for all temporospatial parameters. There are visible differences in the trunk kinematics, specifically for trunk/thorax tilt, where an offset is seen, and a slight variation in trunk/thorax obliquity.
Conclusion: Considering the movement of the spine, these results are expected as the upper body moves differently from the whole trunk through the gait cycle. Furthermore, the report shows the importance of knowing which model is used, as a different model might show different results that are still valid.

Acknowledgements

I would like to give big thanks to my two supervisors, Roy Tranberg and Roland Zügner, for their support, kindness and answering every question I could ask. I would also like to thank Kerstin Lagerstrand and Helena Brisby for their input and relevant critique. To Lydia Dahlgren for her help during the measurements and to all my friends, family and colleagues at the Lundberg Laboratory for participating in the measurements and your support. To Christoffer Palmberg for agreeing to be my opponent and writing a very nice opposition which was a pleasure to read. And lastly, thank you Sabine Reinfeldt, my examiner, for your help and kindness.

Maria Sundström, Gothenburg, November 2018

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1
Introduction

Gait analysis is a useful tool when treating various diseases affecting the motor-functions of the body [1]. Three dimensional (3D) gait analysis is widely used for the lower body examining Cerebral Palsy, stroke and other diagnoses affecting gait. As mentioned, even though the main focus is on the lower body, looking at the leg movement and rotations, but the 3D motion capture technique can nowadays include most of the body with good precision and full body gait analysis can be done [2] [3] [4]. Stroke [5] or spastic diplegia [6] [7] are some of the diseases that can benefit from a focus on trunk kinematics when performing gait analysis, but the research concerning 3D gait analysis of the trunk is much less extensive as for the lower body.

3D gait analysis utilizes skin markers to define segments with which you can build a model of a body. There are some different ways to define a segment and therefore there are various skin marker models. The choice of a certain model determines the data you get, how it looks, and the accuracy of that data, and each model has different sources of error. Being aware of these possible errors is important especially when comparing the data with other hospitals' results or research studies.

The marker models have developed over time as knowledge and technology has evolved. One of the most used and popular models is the so called IOR skin marker method, developed by researchers at the Instituti Ortopedici Rizzoli in Italy [8] [9]. Given its popularity it could be advantageous to use the same when doing research, to simplify comparison of data between studies. There has not been much research on comparing marker models to each other and those who have; Ferarri et.al. [10], Collins et.al. [11], Kainz et.al. [12] and Leardini et.al. [13], have not included the Lundberg skin marker model [4], a skin marker model developed at Mölndal's Hospital, Göteborg.

The Lundberg skin marker model for trunk describe the trunk as one rigid body. The IOR model on the other hand has a thorax segment and a possibility for additional information. This thesis aims to compare the Lundberg skin marker model to the IOR skin marker model to analyse what differences there are between a one-segment trunk model compared to a model focused on the thorax. Will the resulting data differ significantly or does it matter which model is used?

2

Theory

2.1 The Gait

The gait is the action in which we walk and can be defined by a variety of parameters and events. The gait cycle encompasses several parts and together they describe the gait in detail. The parameters and events can be used to analyse a disease or injury by using gait analysis.

2.1.1 The Gait Cycle

> "The gait cycle is defined as the time interval between two successive occurrences of one of the repetitive events of walking."

The definition above was written by Whittle in 1991 and the mentioned occurences can be any chosen event, but the most frequently used is heel strike/initial contact. The rest of the events in the gait cycle are briefly described below as described by Whittle [14].

Heel Contact: Also called *Heel strike*, and is the moment the heel touches the floor, an event detected by a force plate. This is the beginning of the *stance phase*.
Foot Flat: The entire foot flat on the floor.
Mid Stance: The feet are now parallel with the foot in focus on the ground.
Heel Off: The heel leave the floor.
Toe Off: The whole foot has left the floor. This is the end of the stance phase and at the same time the beginning of the swing phase.
Mid Swing: Both feet are parallel with the concerned foot in swing phase (above ground). [14]

The gait can be defined by *stance* and *swing phases*. The first five events are in the stance phase, which can also be called *support phase* or *contact phase*, as the foot is fully or partially on the ground. *Toe off* is the link between the *stance phase* and the *swing phase* as the foot leaves the ground and does no longer support the body weight. And similarly *heel contact* is the link between the *swing phase* and the *stance phase* as the foot touches the ground and begin to bear the weight.[14]

When walking the trunk moves cyclically, upright to more bent, from right to left or rotation. In the sagittal plane, side view, the trunk has its highest position just before double support and will immediately switch to the highest position directly after double support. In the frontal plane, the trunk can be seen to move from side to side while walking and the switch, again, seem to be during double support with the bend towards the swing leg. Finally, in the coronal plane, the trunk rotates towards the swing leg with, again, a change in direction during double support. This is repeated for every gait cycle. [15]

When speaking of the different phases and stages in the gait one is almost always only considering one leg at a time. But one has to remember that all of the events happen for both legs. When one leg is in mid swing, the other is planted on the ground for support. There is a small period when both feet are planted on the ground, so called double support, between heel contact of one foot to the toe off of the other foot. As the *stance phase* is longer than the *swing phase* the *stance phases* for the two legs must overlap at some point, and thus double support.

2.1.2 Determinants of Gait

In 1953, Saunders et al. [16] described that the core of the human gait is how the center of mass (COM) moves and that the gait is optimized to minimize the displacement of the COM while walking. To describe this, he proposed six determinants of gait and that these determinants would work together to minimize COM displacement. He also introduced so called *compass gait* with which he explained the six determinants and their use. Compass gait is described as a lower body consisting of rigid sticks, without any hip-, knee- or ankle joints and the resulting gait would be (vertically) sinusoidal with quite high peaks. This would result in a very stiff gait. Introduce hip joints and the gait would be more smooth, a lower amplitude of the sinus curve. Here the determinants *pelvic rotation* and *pelvic tilt* are introduced. They reduce the height with which the COM would have to be elevated. The rotation elevates the pelvis and flatten the curve. Pelvic tilt combined with *knee flexion (in stance phase)* (adding a knee joint) flattens the curve even more. The rest of the determinants are the *knee-* and *foot mechanism* and the last one is *lateral displacement of the pelvis.*

This explanation of gait was accepted for a long time, but has since been questioned [17]. Researchers have looked into the different determinants and their effect of reducing the displacement of COM, and reported that some determinants are not as important to the gait as reported by Saunders et.al., [18] [19], or maybe even has a different purpose all together (e.g. the function of knee flexion is primarily chock absorption) [20] [21].

Even though Saunders explanation might not have been the whole truth to human gait, minimizing the energy to walk is still relevant. As the trunk and the upper body consists of over half of the body's total weight, a faulty displacement of the trunk can have consequences on the gait. The stance changes as the body compensates to save energy and keep balance. A displacement of the trunk shows that the energy required for balance and muscular demand when walking increases [22] and the body will change its posture to save energy. This compensatory change in posture has been reproduced in able-bodied subjects as well as subjects with spinal diseases [23] [24] [22].

2.1.3 Temporospatial Parameters

There are a lot of factors to take into account when analyzing patients gait clinically. To narrow down the amount of data one could merely analyze the so called temporospatial parameters, or spatiotemporal. The temporospatial parameters describe discrete parameters, as the name implies, relative to the room (spatial) or time (temporal). More parameters, such as foot strike, foot off and step time, could be considered [25]. These temporospatial parameters are however only examined briefly in this report. A short explanation of the different parameters follow below:

Cadence is measured in steps per minute and is the rate at which a person walks.
Stride is the distance between two successive placements of the same foot, for example from left heel strike to the next left heel strike. It can also be said to be equal to two step lengths. [14] It is measured in meters.
Velocity or speed is measured in meters per second and counts the covered distance by the body during a certain time interval. Velocity for example can also be calculated using cadence and stride with the equation below [14].

$$velocity\ (m/s) = stride\ length\ (m) * cadence\ (steps/min) * \frac{1}{120} \tag{2.1}$$

Step length is the distance between left or right foot placement and right or left foot placement and which is, as mentioned, half a stride length. It is measured in meters.
Symmetry is calculated by using the right and left stance time and cycle time of the gait and is a measure of the similarities between the the two sides, right and left. It is calculated using different quotes, right and left stance quote being quotes between the stance time and cycle time for each leg. Together a ratio for symmetry is calculated:

$$\frac{left\ stance\ quote}{right\ stance\ quote} * 100\% \tag{2.2}$$

This quote indicate a true symmetry when it equals 1. There are other so called symmetry factors such as symmetry index, gait asymmetry and symmetry angle [26], but equation 2.2 will be the one used in this report.

2.2 The Kinetics and Kinematics of Gait

Kinetics describe forces and what those forces put in motion. Kinetic analysis could be done using force plates. To analyse someones gait in this way a Butterfly diagram, or Pedotti diagram, which displays the forces during stance phase can be used. The kinematics, on the other hand, describe motion without the use of forces. Instead the motion of segments, defined by coordinates, are calculated. The division of the body into different segments is the basis for kinematic gait analysis [27]. The rigid segments are defined by markers attached to the body, allowing video tracking and 3D motion capture. The cameras and markers together makes it possible to make kinematic calculations of the joints and limbs.

Although both kinematics and kinetics can be used separately, they benefit greatly to be used together. One of the advantages with using both is the more accurate measurement of events like toe-off. This is a bit tricky to calculate exactly with cameras and markers alone, but force plates can measure such events. Event detection using force plates are done by having a threshold to tell how much force, measured in Newtons, needs to be applied for the force plates to start to measure that event, and similarly, when that event has ended. Together, kinetics and kinematics can also calculate moments and power of joints which can be used for analysis.

2.3 Gait Analysis

When doing gait analysis some simplifications need to be made, since the human locomotion with the many bones and joints cooperating to produce the gait is complex. One of these simplifications is that the body is approximated with a number of segments, representing the different body parts. Body parts that include joints, such as the spine or foot, can be approximated into a single segment, a so called rigid-body representation. For the lower body, the approximation is quite good as a rigid segment for the shank and thigh is not that far from the truth. Making a single segment of the trunk, however, is creating a simple but rough estimation. The trunk includes the spine, which in turn consists of 24 vertebrae (not including the sacral vertebrae). These vertebrae move and make the trunk flexible, and to keep the trunk a single segment could therefore be a bad choice [28]. Though, it depends on how accurate the measurements need to be. Few segments of the trunk (maybe 1) could suffice when doing certain research, or in clinical practice that do not concern the trunk [13], while more segments are required for a better representation [29].

2.3.1 The motion capture technology

When creating a body in 3D space, it is simplified into segments. These segments are defined with markers, which are tracked by cameras. At least two cameras are needed to triangulate a point in 3D-space but for a complete model of a body there are several cameras situated around the room for complete coverage of the subject, figure 2.1.
For angular measurements, the body is compared to the coordinate system of the environment. The most common way is to have the pelvis segment defined against the room coordinates, the global coordinates. The thigh is then defined against the pelvis, and the shank against the thigh. The principle is that every segment is defined to its neighbour closest in the pelvis direction.

The markers are nowadays coated with a reflective coating which makes it easier for the cameras to see only the markers. For segment definition calculated virtual markers can also be used, which can for example define the hip joint which cannot be marked by a physical marker. The markers can have different size, depending on

the resolution of the cameras, and with more precise cameras the markers can be very small (a few mm). Markers can be placed directly on the skin, in a cluster, or a distance away from the skin, on a so called wand.
Another, quite different, kind of markers are the ones used in roentgen stereophotogrametric analysis, RSA. They are metallic markers implanted in the bone and are used together with roentgen cameras.

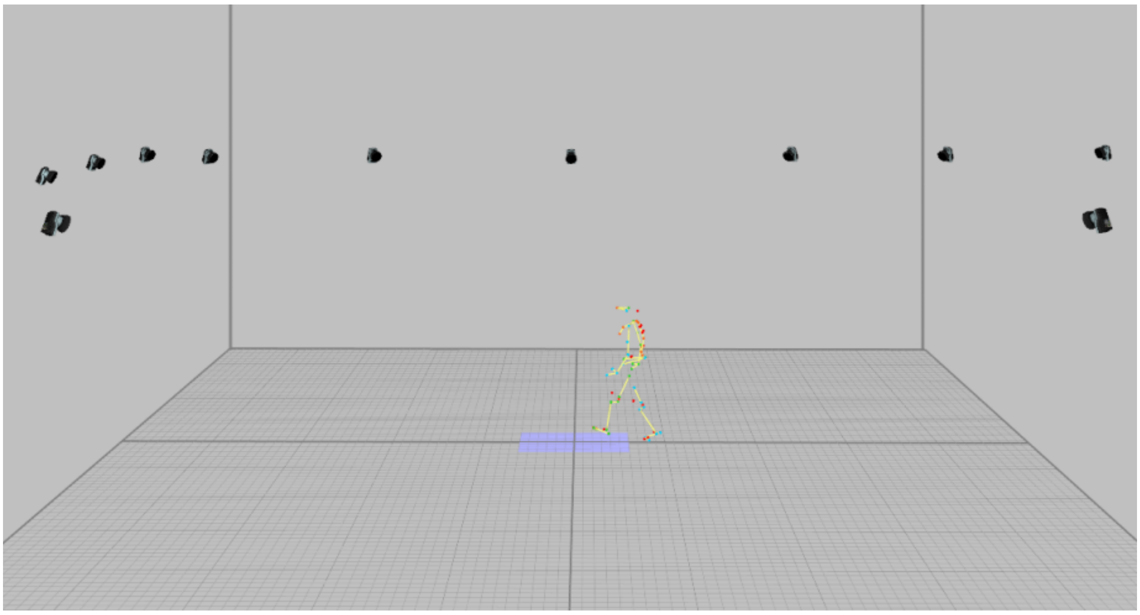


Figure 2.1: The measuring space with cameras mounted on the walls and four force plates sunken into the floor

Soft Tissue Artifact
Most methods tracking the skeleton landmarks use markers on the body directly on the skin. This becomes a problem when the subject starts to move and cause errors known as soft tissue artifacts (STAs), and could be complex errors not easily dealt with [30]. Previously, the STAs have been difficult to reduce [31], but there are possible new solutions using algorithms to minimize them. Other sources of error could simply be occlusion of certain markers, especially markers at the anterior superior illiac spine (ASIS) [32] with overweight or obese patients.

2.3.2 Skin marker models

A skin marker model is the way markers are distributed on the body for the purpose of gait analysis. The markers are usually placed on well defined anatomical landmarks [33], but marker placement can differ and be customized the way the researcher or clinician wants.

Roentgen Stereophotogrametric Analysis
The technique roentgen stereophotogrametric analysis (RSA) is considered the golden standard thanks to its high accuracy. It is used clinically, mostly with patients that

has had a hip replacement surgery or cruciate ligament replacements. The method use roentgen cameras and reference frames to determine the position of tantalum markers in implanted into the bones [34]. The method is invasive and you expose the patient to X-rays, but in turn you get a very accurate position of an implanted prosthesis and the true skeletal movement.

3 vs. 6 Degrees of Freedom
Defining the segments of the body can be done in a variety of ways depending on the marker placement. The simplest version have all joints attached to the next segment. However, some joints do not apply this version. The knee-joint for example does not only have a rotation in the joint center, but also a translation, making the simple version with joint segments a faulty model.

The segments that are joint together has 3 degrees of freedom (3DOF) allowing them to rotate in all three directions. Segments that are not joint can have 6 degrees of freedom (6DOF) allowing for translations as well as free movement. 3DOF models can cause chain effect of errors as a computational error in the hip can cause even worse error down in the foot.

2.3.2.1 IOR skin marker model

The IOR skin marker model, figure 2.2 and figure B.1, was made by researches from the Instituti Ortopedici Rizzoli in Bologna and can be divided into a lower body part and a trunk part. The lower body marker model was made with the objective to make an easy model for gait analysis in children, specifically children with Cerebral Palsy [9]. The trunk marker model was developed with focus on an accurate depiction of the thorax and spine, a semi-multi-segment model, as the model consist of a 3D thorax segment as well as one shoulder line and 3 spine 2D segments.

The full-body model is a combination of the lower-body model and the trunk model, with additions made by Qualisys AB, Göteborg, Sweden. These additions are arms and head to make visualization easier giving a complete body and not just a trunk and legs. IOR was slightly modified for the marker at the great trochanter. This modification was done by Qualisys to make the model easier to work with. The trochanter marker was moved down the femur to give the patients the ability to wear more comfortable clothing as the marker doesn't have to be as high up. The marker was moved a third distally on the femur. As the marker is only used to track the thigh segment and not define the coordinate system, the placement is not as important.

The different segments that are defined are foot, shank, thigh, pelvis, thorax and a shoulderline. They are defined by the following markers:

Trunk: The model uses ten markers for the trunk. The 2nd thoratic vertebrae (TH2), MAI, the sternum at the jugular notch (IJ) and the xiphisternal joint (PX) make up the thorax segment. PX, MAI and IJ create a plane and a Z-axis (upward pointing) is created between MAI and TH2. The segment rotates around MAI and has a proximal point at MAI and a distal point at TH2.

The shoulders are defined by the left and right acromial edge of the scapulae (SAE), creating a shoulderline, and the spine is marked with three lumbar markers, L1, L3 and L5.

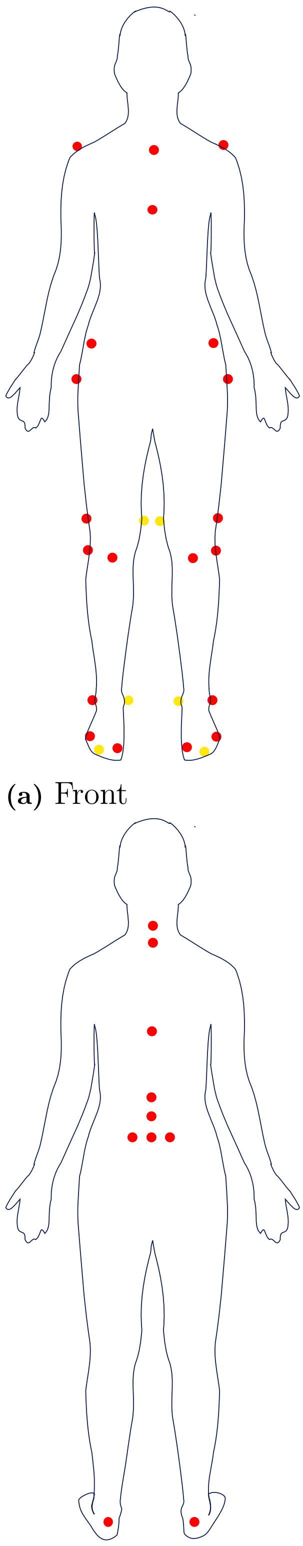
The IOR model creates a semi-multi-segment trunk model. The thorax can work together with the shoulderline segment as well as the lumbar markers, but can also work separate from these 2D elements. This gives additional kinematic information for a more complete view of the trunk.

Pelvis: The pelvis segment is a Coda pelvis [35], consisting of four markers; right and left ASIS (anterior superior illiac spine) as well as right and left PSIS (posterior superior illiac spine). The PSIS markers are used to create a virtual marker at the point halfway between right and left PSIS.

Thigh: Three markers are used for the thigh segment. The segment is defined with a virtual marker at the hip joint as well as the medial and lateral femural epicondyle (FME and FLE). FME is a static marker. A marker on the great trochanter (FTC) is used for tracking. This marker has been moved further down, by Qualisys, on the femur for easier access.

Shank: Four markers, proximal tip of the head of the fibula (FAX), most anterior border of the tibial tuberosity (TTC), lateral and medial prominence of the lateral malleolus (FAL and TAM), are used for defining the shank, where TAM is a static marker and the rest are tracking markers. The segment rotation centre an proximal end is in a virtual marker located in the knee joint. The ankle joint defines the distal part of the segment.

Foot: Four markers, dorsal margin of the first, second and fifth metatarsal head (FM1, FM2, FM5) and aspect of the achilles tendon insertion on the calcaneus (FCC) make up the physical markers put on the foot, where FM2 is a static



(a) Front

(b) Back

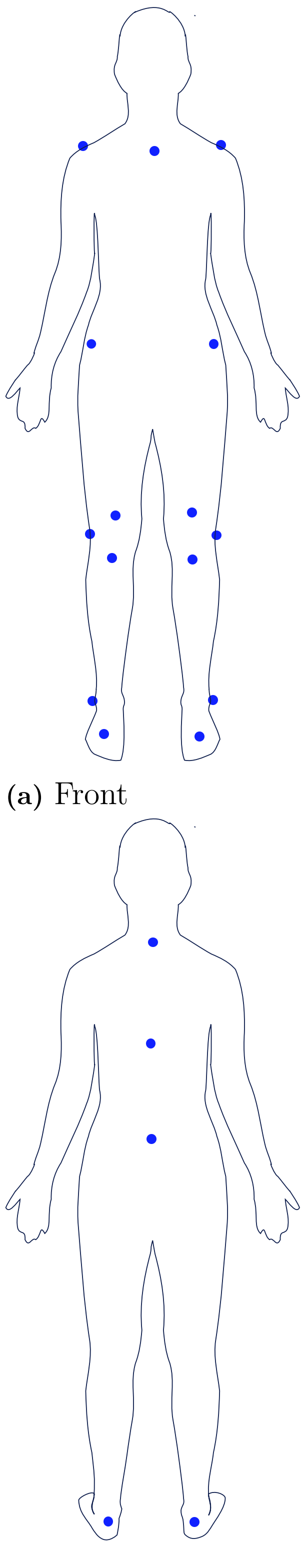
Figure 2.2: The IOR skin marker model for trunk and lower body. Yellow dots are static markers.

markers and the other are tracking markers. The segment is a cylinder with a distal end at FM1 and FM5 and a proximal end at a virtual ankle centre. Segment centre is located in the ankle, with a virtual marker. FM1, FM5 and the virtual ankle marker form a plane from which the coordinate system is derived. [9][36]

Parts added by Qualisys to make a complete skeleton for animation are, as previously mentioned, arms and head. These will not be included in the analysis and were not developed as a part of the model. They will therefore not be described further.

2.3.2.2 Lundberg skin marker model

The Lundberg skin marker model, figure 2.3 and B.2, was developed at the Lundberg Laboratory in Mölndal. It has been used extensively with children, and therefore developed to be as simple as possible. The model is mostly used for the lower body, where it has been validated against RSA. Expanding the model to include trunk would give additional data for movement during walking and the relations between lower and upper body.



(a) Front

(b) Back

Figure 2.3: The Lundberg skin marker model for trunk and lower body.

The marker positions and segments used in this model are:

Trunk: The trunk is defined by the sternum, TH2 and TH12 marker. Rotation center as well as the coordinate systems origin is defined by a virtual marker calculated with sternum and TH2 marker and is also the proximal point of the segment. Distal points are the right and left ASIS markers. No specific thorax segment is defined, like the IOR model have.

The shoulders are defined by markers on the left and right acromial edge of the scapulae. These markers calculate the location of the shoulder joint. The shoulders are mainly defined to give additional information of the upper body movement and are not technically a part of the trunk marker model.

Pelvis: The pelvis segment is a modified Coda pelvis [4]. The two markers at the left and right PSIS are changed to a single marker at the midpoint of the previous two, at the sacrum. The two markers at left and right ASIS are unchanged. These markers define the coordinate system as well as the calculated hip-joint centers.

Thigh: The thigh is defined with a virtual hip marker, knee joint line (KJL) and the supra pattellar marker (SUPPAT). The hip marker is calculated with the ASIS marker. [4]

Shank: The shank is defined with the markers for the ankle, KJL and tibial tuberosity (TUBTIB). The proximal point is defined with a virtual marker at the knee, created from KJL, FAL and TUBTIB, and the distal point is defined by the ankle marker. [4]

Foot: The foot is defined with a proximal point as well as rotation center with a virtual marker at the ankle, calculated from the heel marker, and a distal point at the 2:nd metatarsal head (TOE). The heel marker is used as well for additional information about orientation. [4]

As for the IOR marker model, the Lundberg skin marker model does not define arms or head and these segments are added by Qualisys for a more complete model. As previously, they will not be described further.

2.4 Clinical Applications for Trunk Kinematics

Most gait research has been focused on the lower body, and lately there is more research of how the trunk movements play a role in the body's stability in gait and movement [7]. The trunk affects the gait pattern and helps balancing the body during walking and other movements [15]. The thorax and pelvis oscillate, and helps to counter the movements of the lower limbs during leg swing [37]. Movements of trunk and pelvis differ for different velocities [38]. A change in posture (different trunk angle etc), due to a disease or injury, can affect the lower body with changed hip, knee and ankle angles. The body compensates for the changed conditions to make the best of the situation. The knowledge about that kind of change can help clinicians in their analysis. [24]

3

Methods

3.1 Marker models

The two models that are to be compared are the Lundberg skin marker model and the IOR skin marker model, both for full body.
To be able to measure both of the models at the exact same conditions, a hybrid marker model was created. The hybrid marker model consists all markers from both models mixed together and can be seen in figure 3.1. Some marker positions were the same for both models, and the rest could be placed without interference with the other model, with only two exceptions. The markers L5 and sacrum were merged to one marker position, and L1 and Th12 were merged together as one as well, see figures 2.2, 2.3 and B.3. The markers were then placed for all subjects according to this new hybrid model.

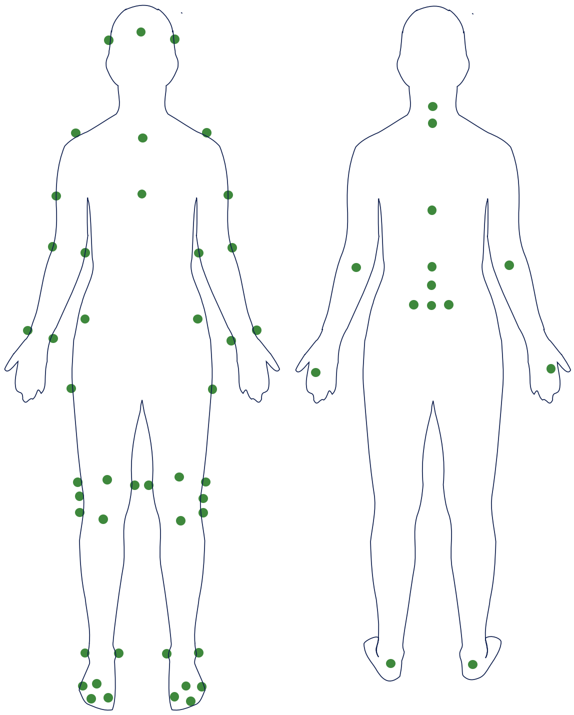


Figure 3.1: The hybrid marker model used for measurements. Front and back, respectively.

3.1.1 Marker placement

The skin markers were placed on the body using double adhesive tape, which was later thrown away as only the skin markers are reusable. The markers, spherical plastic balls of size 12mm with a reflective coating provided by Qualisys AB, were only changed once as the reflective coating/surface were worn down. The head markers were positioned using a headband with the markers already attached.
Markers were placed under supervision of an expert with more than 20 years of experience in the field. The markers were placed while the subject was standing and they were placed on specific anatomical positions [33] according to the hybrid model created. These were as follows:
Head: The glabella (SGL), right and left side of the head just above the ear. These markers were fastened with an elastic band with the markers already attached, fig 3.2.

Arms and Shoulder: Right and left acromial edge of the scapulae (SAE), right and left deltoid tuberosity (HUM), right and left medial and lateral epicondyle (HME and HLE), right and left superior olecranon (SOL), styloid process of ulna (USP) and radius (RSP), basis of forefinger (HM2).
Trunk: The sternum at the jugular notch (SJN) and the xiphisternal joint (SXS), the 7th cervical vertebrae (CV7), 2nd thoratic vertebrae (TH2), MAI, 12th thoratic vertebrae/1st (TH12/L1), 3rd (L3) and 5th lumbar vertebrae (L5/sacrum).
Pelvis: The right and left anterior superior iliac spine (ASIS), the right and left posterior iliac spine (PSIS).
Legs: Lateral side of the great trochanter a third from proximal end for right and left (FTC), right and left supra patellart (SUPPAT), right and left lateral and medial epiconyl of the femur (FLE and FME), right and left knee joint line (KJL), right and left tibial tuberosity (TTC).
Feet: right and left aspect of the achilles tendon insertion on the calceanus (FCC), right and left lateral prominens of the lateral malleolus (FAL), right and left medial prominens of the medial malleolus (TAM), right and left dorsal margin of the 1st, 2nd and 5th metatarsal head (FM1, FM2 and FM5), right and left dorsal proximal point of the 2nd metatarsal bone (TOE).

Figure 3.2: The marker placement on subject with the hybrid skin marker model.

3.2 Test setup and data collection

33 subjects were collected among the author's family and friends as well as colleagues at the Lundberg laboratory. Two subjects were excluded for analysis due to technical issues with the markers. The final subject demographic can be seen in table 3.1. The subjects had a medically healthy gait with no recent injuries or problems.
The subjects were asked to present themselves in either underwear, small sportswear or swimming trunks/bikini. Their height and weight were measured and were documented in QTM (Qualisys AB).

Table 3.1: The final age and sex demographic of the subjects after removal of two subjects.

Subject demographic - Final					
Sex	Amount	Age Span [years]	Median Age [years]	Mean Age $\pm st.dev.$ [years]	BMI $\pm st.dev.$ [kg/m^2]
Men	13	20 - 74	58	47.1 ±19.9	24.9 ±4.4
Women	18	13 - 70	41	42.8 ±18.7	25.1 ±4.8
Total	31	13 - 74	44	44.5 ±19	25 ±4.5

3.2.1 Equipment

The tests were done in a gait laboratory at Lundberg laboratory, Mölndal's Hospital. The room is equipped with force plates (Amti, USA) sunken into the floor. A set of 16 cameras, Oqus 7+, Qualisys AB, Göteborg, Sweden, are set up around the room creating a calibrated volume in which the subject or patient walk within.

The measurements are done using Qualisys Track Manager (QTM), Qualisys AB, Göteborg, Sweden. For calculations of kinematic variables (Euler angles) the Visual 3D™ software (C-Motion, Inc., Germatown, USA) was used.

The measurements were done for both models at the same time and the two marker models were later separated manually in QTM.

3.2.2 Measuring procedure

After all of the markers were placed on the subject, two calibrations was made as IOR utilizes static markers and two calibrations. The first calibration were static and the subject was asked to stand still a few seconds. The subject was standing with the x-axis of the room aligned with the sagittal plane. The second calibration was dynamic and the subject was asked to move arms and legs.

After calibration, the subjects were instructed to walk normally, straight ahead, with a self-chosen speed through the calibrated volume (fig. 2.1). Information on whether they should hit the force plates were not given as to keep their gait as normal as possible and free from distraction. A few warm-up walks were done to let the subject get familiarized to the situation and be able to produce a normal gait. These walks were not measured. During these walks, the starting-point of the walk were calibrated to make sure the subject hit the force plates correctly. The subject walked barefoot, in one direction only (along positive X-axis) accompanied by a "transport-walk" back around the plates. The measuring were done until six approved walks could be recorded. A walk was approved when each foot hit completely within a force plate.

After the measurements, the markers were removed and the adhesive tape was thrown away.

3.3 Analysis

3.3.1 Data Processing

After the measurements, the two different models were identified in QTM. The models were identified manually as the program at some points could not quite work out which marker that corresponds to which model. This was done for both the IOR and the Lundberg model. The data was controlled and a report for each subject was done and later handled in the Visual3D™ software. Upon the identification of the models, two measurements were excluded as the subjects did not get clean strikes on the force plates, giving two subjects with only 5 acceptable measurements each. Two subjects were also completely excluded, as previously mentioned.
The raw data for pelvis and trunk angles, tilt (movement along the x-axis), obliquity (movement along the y-axis) and rotation (movement along the z-axis), as well as calculated temporospatial parameters were exported from Visual3D and put into MATLAB™ for further analysis. Trunk and thorax angles were calculated with respect to the pelvis.

3.3.2 Statistics

All calculations outside of Visual3D™ was done in MATLAB™ R2017b. All means were plotted for the angles and standard deviation were calculated. For statistical analysis, a few points were chosen, effectively down-sampling the data, to make an approximation of the angle curves. Every 20th data point was chosen resulting in 10 data points for each angle, evenly spread out on the gait progression line. For these data points, standard deviation was calculated as well as a statistical analysis with a two-sample t-test, with a significance level at 99%, between the marker models.

4

Results

The resulting differences between the models for pelvic and trunk/thorax angles, in all three planes, are reported in detail. Additionally, the temporospatial parameters as well as some additional angels are reported. The angles were plotted for a complete gait cycle for all 31 subjects, and detailed information about the figures can be found in table 4.1.

4.1 Pelvis

Tilt: Agreability for tilt between the models was good, figure 4.1a and 4.1b. No visible difference could be seen in the figures and the differences that could be seen in the angular values is small enough to be negligible, table 4.1. The measurements were also visibly paired up (red and blue line), figure 4.1a, showing that the models measure similarly for each patient. However, the inter-subject variability was large.

Obliquity: Agreability for obliquity was good as well. No visible pairs of measurements could be seen, figure 4.1c and figure 4.1d, or other noticeable patterns. The inter-subject variability was not as large as for the pelvic tilt, and the curves are overall very similar as any difference is small enough to be negligible, table 4.1.

Rotation: Similar to the other angles for the pelvis, agreability for pelvic rotation was good. Again, there were visible pairs of measurements, figure 4.1e and figure 4.1f, suggesting that the models measure rotation very similarly. Additionally, like for the rest of the pelvic angles, any difference present is small enough to be negligible, table 4.1. There were also a few measurements that differ substantially from the rest in terms of curve shape, but as the measurements are paired up, the mean curves of the models are still very similar.

4.2 Trunk

Tilt: Trunk/thoratic tilt had a visible offset, figure 4.2a, with statistical significant differences at all times in the gait cycle, figure 4.2b. The offset is around 24° and shows a clear difference between the models.

Obliquity: Trunk/thoratic obliquity on the other hand, had no offset but a variation in the shape of the curve, figure 4.2c. Some parts proved statistically significant, figure 4.2d, although they might not be clinically significant as the subject variability were relatively large (around 10° in some places). IOR has both a higher global maxima and a lower global minima than Lundberg, which can be seen in table 4.1. Lundberg seem to have a greater variability of the curve through the gait's progression with clearer local maxima and local minima, though.

Rotation: Agreability for trunk/thoratic rotation was quite good apart from a slight offset at the second half of the curve with some significantly different points. However, these differences are probably not clinically significant as the inter-subject variablity of the subjects are bigger.

Table 4.1: Table of the 10 chosen data-points. Shown is the angle at the certain point as well as the standard deviation and p-value. All motion is performed in the same direction and negative values indicate an angle below origo. p-values calculated with a two-sample t-test are shown for the points. Bold values are statistically significant, with p<0.01.

	Pelvic Tilt					**Thoratic Tilt**				
	Lundberg		IOR			Lundberg		IOR		
	angle	st.dev.	angle	st.dev.	p-value	angle	st.dev.	angle	st.dev.	p-value
1	6.9	5.3	7.2	5.2	0.869	-15.3	6.9	8.8	7.5	**<0.001**
2	6.4	5.5	6.9	5.3	0.718	-16.3	7.2	7.6	7.8	**<0.001**
3	6.4	5.7	6.6	5.5	0.841	-16	7.4	8	8.0	**<0.001**
4	6.4	5.6	6.7	5.5	0.833	-15.3	7.1	8.4	7.9	**<0.001**
5	6.5	5.3	6.8	5.2	0.801	-14.7	6.5	9	7.5	**<0.001**
6	6.4	5.4	6.7	5.3	0.817	-15.1	6.6	8.6	7.4	**<0.001**
7	5.9	5.5	6.4	5.2	0.746	-15.8	6.7	7.8	7.6	**<0.001**
8	5.9	5.6	6.2	5.5	0.846	-15.6	7.0	8.2	7.9	**<0.001**
9	6.2	5.5	6.5	5.4	0.826	-15.1	6.9	8.5	7.7	**<0.001**
10	6.5	5.3	6.9	5.1	0.808	-14.8	6.6	8.9	7.4	**<0.001**
	Pelvic Obliquity					**Thoratic Obliquity**				
	Lundberg		IOR			Lundberg		IOR		
	angle	st.dev.	angle	st.dev.	p-value	angle	st.dev.	angle	st.dev.	p-value
1	-0.4	1.8	-1.4	1.5	0.025	2.7	2.2	-0.3	1.9	**<0.001**
2	2.5	2.0	1.8	1.8	0.148	-2.7	2	-4.1	2	**0.007**
3	2.5	2.0	2.2	1.9	0.564	-3.2	1.8	-4	2.1	0.101
4	0.3	2.1	0.2	1.9	0.855	-1.3	2.1	-0.2	2.5	0.100
5	-0.3	1.9	0.1	1.9	0.495	-2.1	2.2	1.3	2.6	**<0.001**
6	-0.1	1.7	0.6	1.7	0.116	-2.6	2.1	2.1	2.6	**<0.001**
7	-2.9	1.8	-2.5	1.7	0.347	2.7	2.3	6	2.6	**<0.001**
8	-2.8	1.7	-2.8	1.7	0.947	3.2	2.2	5.7	2.3	**<0.001**
9	-0.9	1.3	-1	1.3	0.699	1.5	1.9	2.2	1.9	0.117
10	-0.1	1.5	-0.7	1.3	0.107	2.1	1.9	0.4	1.8	**<0.001**
	Pelvic Rotation					**Thoratic Rotation**				
	Lundberg		IOR			Lundberg		IOR		
	angle	st.dev.	angle	st.dev.	p-value	angle	st.dev.	angle	st.dev.	p-value
1	5.3	3.4	5.4	3.4	0.931	-5.7	3.3	-7.1	4.1	0.126
2	3.8	2.8	4.1	2.8	0.660	-5	2.8	-4.4	3.6	0.462
3	4.1	2.3	4.4	2.3	0.599	-2.9	2.2	-2.1	3.0	0.287
4	2.7	2.4	2.9	2.4	0.759	1	2.5	0.9	3	0.875
5	-0.3	2.8	-0.2	2.7	0.915	4.3	2.6	4.2	3.2	0.855
6	-3.1	2.9	-3.1	2.9	0.998	6.6	2.7	6.4	3.4	0.834
7	-1.5	2.4	-1.6	2.4	0.767	5.9	2.7	3.8	3.1	**0.004**
8	-1.6	2.2	-1.8	2.3	0.801	3.6	2.3	1.4	3.1	**0.002**
9	-0.3	2.6	-0.4	2.6	0.889	-0.0	2.5	-1.5	3.2	0.045
10	2.9	3.2	2.8	3.2	0.948	-3.4	2.9	-4.8	3.6	0.092

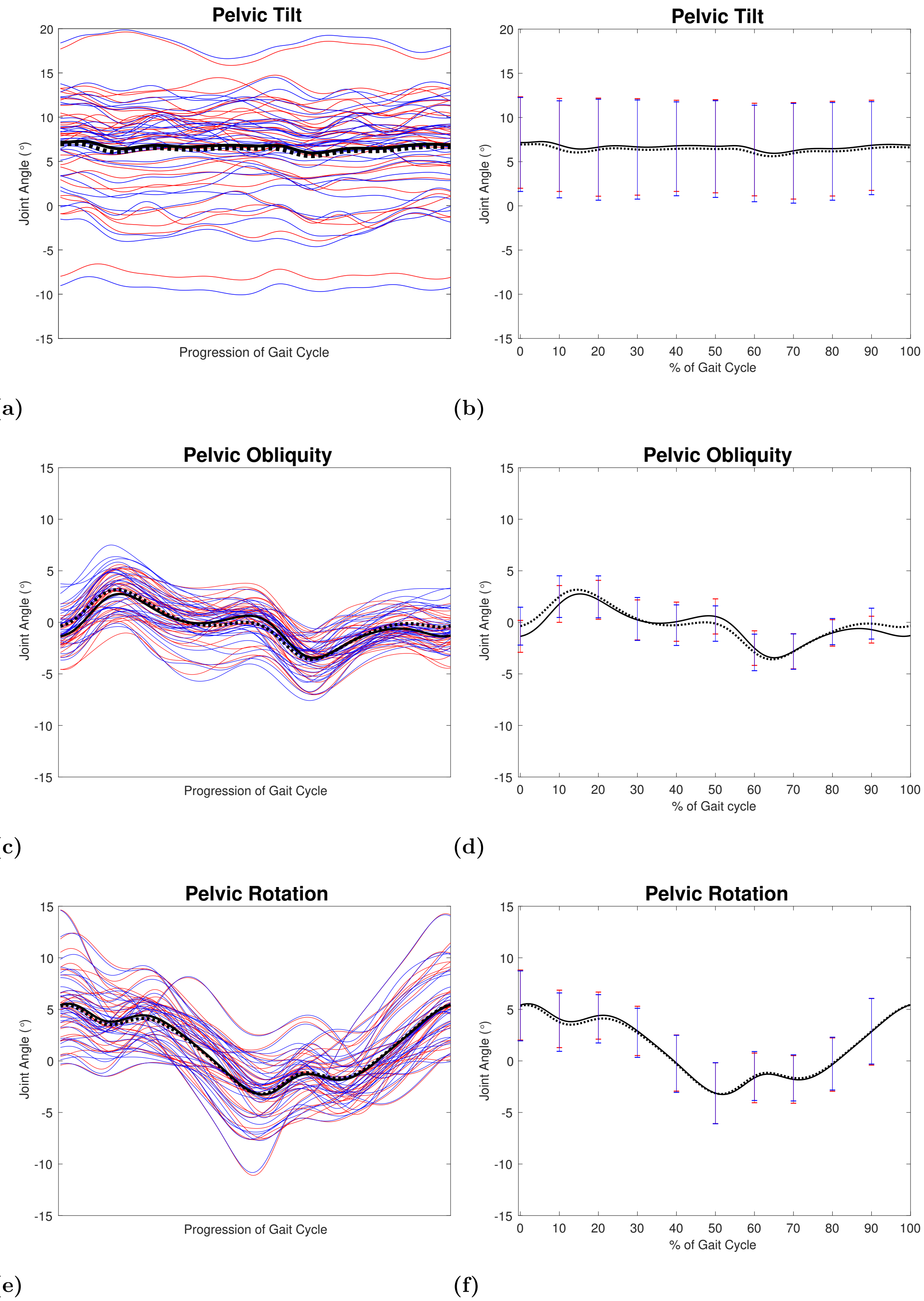
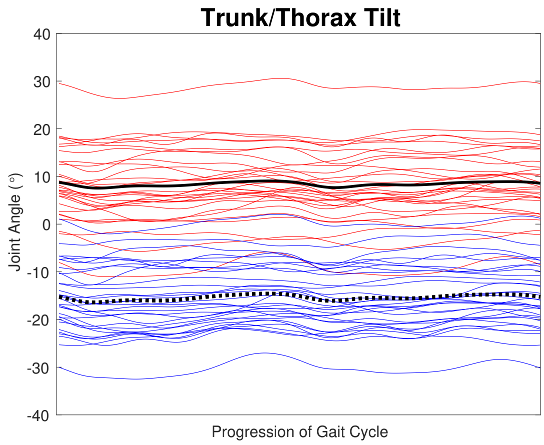
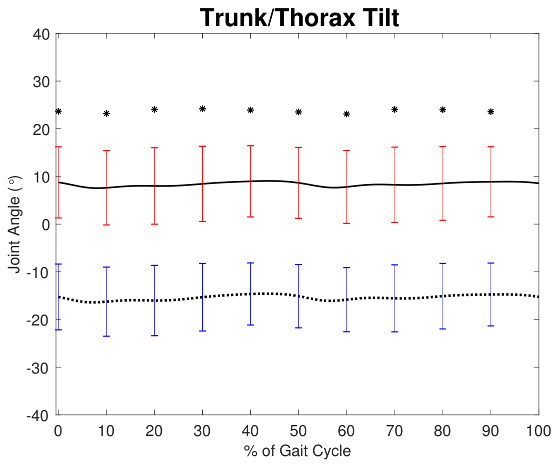
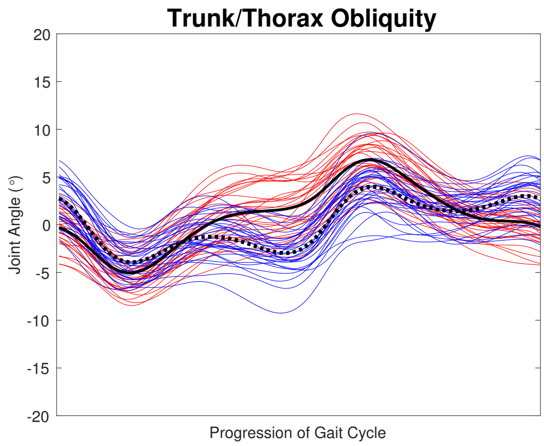


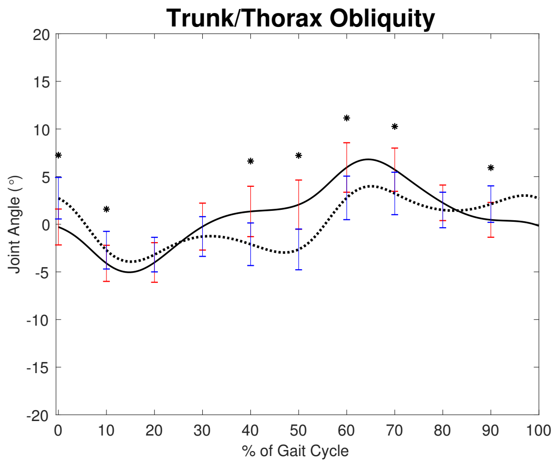
Figure 4.1: Figure a, c and e show plots for pelvic angles with subject means (red for IOR and blue for Lundberg) and model mean (solid line for IOR and dotted line for Lundberg). Figure b, d and f show plots for model mean with ± 1 st.dev. at the 10 chosen points. The standard deviation were calculated using the subject means at the chosen points. Statistically significant points are denoted with *.



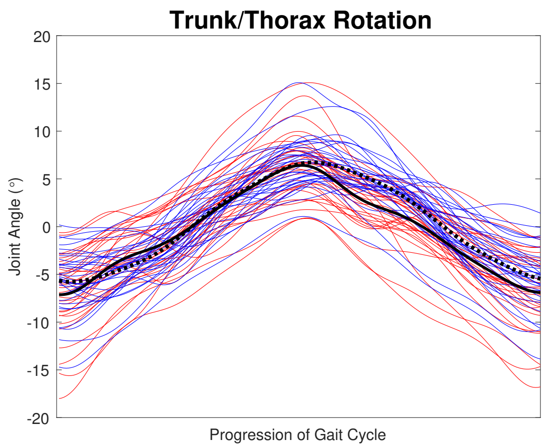


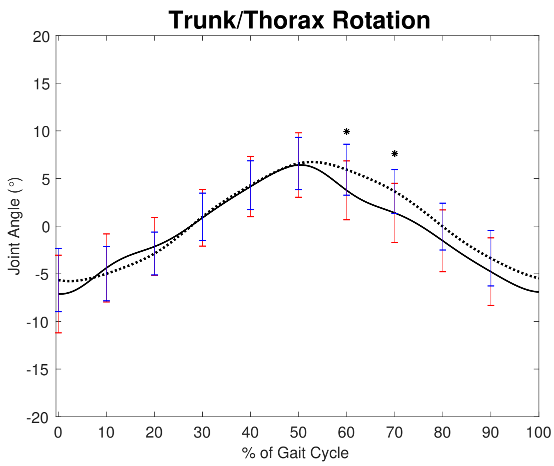
(a) **(b)**





(c) **(d)**



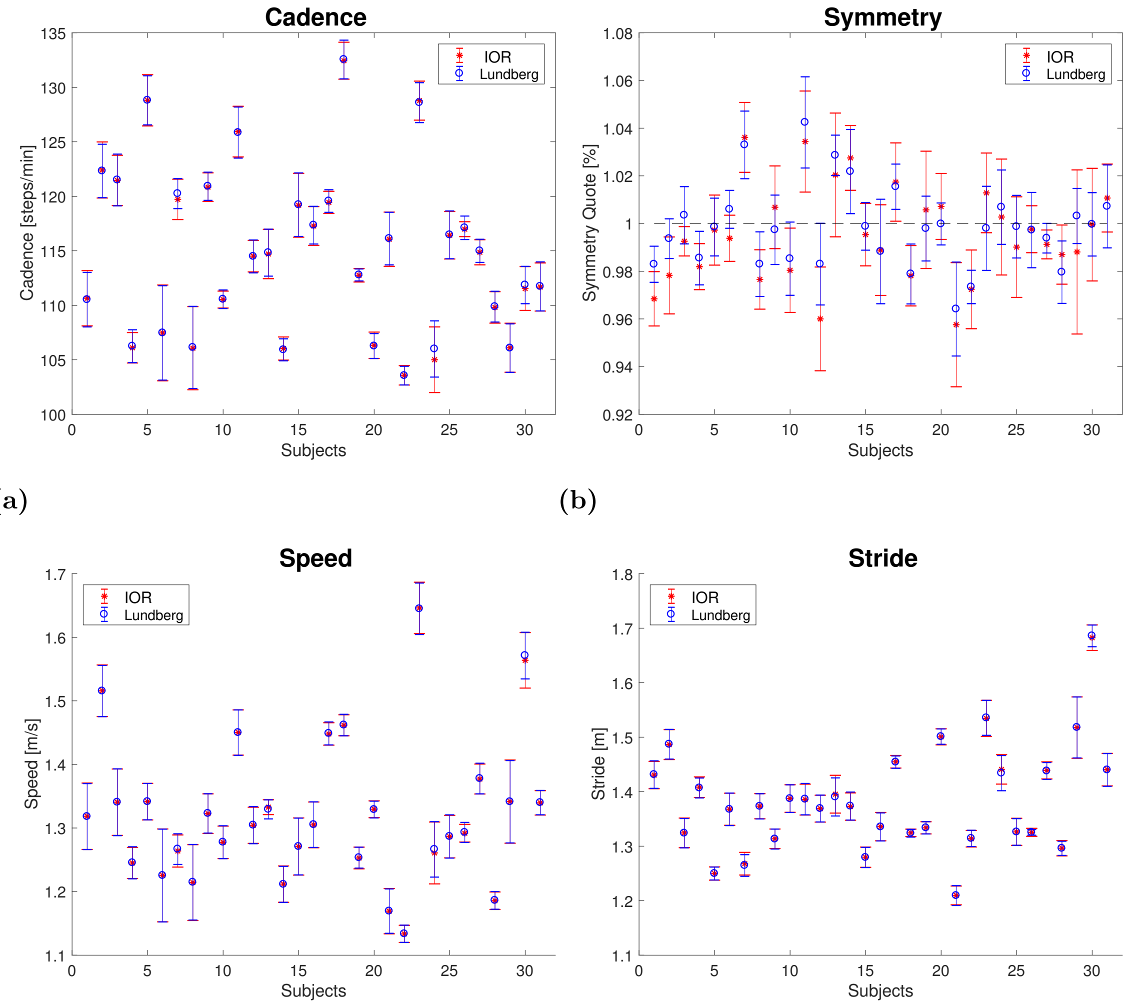


(e) **(f)**

Figure 4.2: Figure a, c and e show plots for thoratic angles with subject means (red for IOR and blue for Lundberg) and model mean (solid line for IOR and dotted line for Lundberg). Figure b, d and f show plots for model mean with ± 1 st.dev. at the 10 chosen points. The standard deviation were calculated using the subject means at the chosen points. Statistically significant points are denoted with *.

4.3 Overall model comparisons

Temperospatial parameters
The temporospatial parameters that were analysed were *cadence*, figure 4.3a, *symmetry*, figure 4.3b, *speed*, figure 4.3c, and *stride*, figure 4.3d, and no clear difference between the models could be found. A slight variation could be seen regarding symmetry, figure 4.3b, but these effects could be due to the difference in event thresholds between the models, discussed in section 2.2. The difference is minimal, but could be exaggerated due to the calculation steps involved in symmetry. Although, as the variations are very small it could be considered insignificant.



(a) (b) (c) (d)

Figure 4.3: The Temporospatial parameters plotted with their standard deviation. The Lundberg model is shown with ∘ in blue and the IOR model with * in red. The data is shown with ± 1 st.dev.

Additional Results

Additional parameters was briefly evaluated (Appendix A). Angles included are hip flexion, hip adduction, knee flexion and ankle flexion. These did not show any clear difference between the models, apart from ankle flexion which seemed to have an offset of a few degrees. Moments and power for hip, knee and ankle was also plotted and no clear difference could be seen.

5
Discussion

This thesis explores the differences between two skin marker models. The comparison is done to deepen the knowledge of the difference that a choice of marker model and segment definition can make. Previously, some comparisons have been done that include the IOR marker model [10] [39], but the amount of studies done to compare marker models are scarce to the author's knowledge and none has included the Lundberg skin marker model. Clinically, such a comparison can be very important when comparing results, to avoid confusion and to better understand results from other research.

5.1 Trunk Angles

There is a difference between what is statistically significant and clinically significant. On one hand, the math can show that data differ significantly, but, on the other hand, if the data overall do not differ that much, the significant difference does not need to be clinically important. A difference in a few degrees could look like a lot when the curve overall does not change much but can be completely normal and from a healthy gait.

5.1.1 Pelvis

The pelvis angles did not differ a lot between the marker models. Both of the marker models define the pelvis almost identically, where the only difference lie in that IOR uses the calculated point between left and right PSIS marker, while the Lundberg marker model skip the calculations and simply put a marker at that same mid-point. This similarity is evident in both tilt and rotation as the curves are paired between models, showing that IOR and Lundberg measure very similarly. For obliquity there is no such pairing, at least not as visible. The reason for this is unknown, but an explanation could be that the calculation step of the PSIS mid-point changes the data enough to not "pair-up" with the other models data. This calculated, virtual marker might have a slightly different position from the actually placed marker for Lundberg, possibly resulting in two slightly different pelvis segments. Any other explanation could not be found as of yet and would need further examination of how the segments are defined and calculated in Visual3D.

Some curves for pelvic rotation were visibly different from the rest. The cause of this is unknown as no abnormal gait patterns could be found for those subjects.

And as the aim for this report is to compare the models, the shape of the curve of a healthy subject is not the concern, but still worth mentioning.

5.1.2 Thorax

For the thorax tilt there is a visible offset between the model. This offset is probably due to that the different segments (thorax and trunk) have their coordinate systems placed at different points on the spine and therefore different origins from where angle measurements are done, see fig. 5.1. The data thus shows that the tilt of the thorax and trunk segments are very similar, as in very small changes in angle during walking. These small changes in tilt angle has also been shown by Ceccato et.al. [15]. Apart from the offset, the curves are very similar and if the clinician have this offset in mind, then the models could be used interchangeably.

When subtracting the models from each other, the inter-subject variability range from 15° to 31°. When aligning the means (25° added to Lundberg curves) the inter-subject difference is around ± 8°. If the curves would have been paired, like for the pelvic tilt and rotation, the difference would be close to zero. This difference that is present in the trunk/thorax tilt data shows that the data is significantly different and perhaps that the trunk/thorax marker models are not quite that interchangeable.

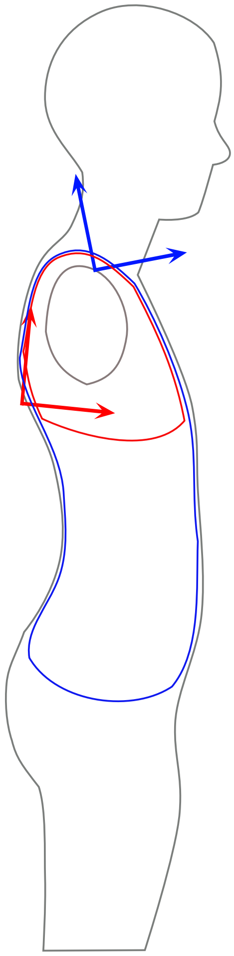


Figure 5.1: The trunk and thorax segments and their respective coordinate system. The Lundberg trunk segment in blue and the IOR thorax segment in red.

Obliquity showed a difference in curve-shape. This might be explained by the different movements along the spine during walking, combined with the fact that the angle-origins are situated at different parts of the spine, fig. 5.1. The trunk does not move like a pendulum, swinging from the hips, but have more range of motion in the frontal plane (obliquity) in the middle of the spine than at the neck [15]. The lumbar vertebrae are more suitable for flexion/extension than rotation, in contrast to the thoratic vertebrae that are more suitable for rotation and tilt in the frontal plane (here obliquity) [40]. This might explain the difference in curve shape in the graphs, fig. 4.2c, with a larger angle range for the IOR model than for the Lundberg model. The difference is statistically significant and, depending on use, could be clinically significant. If there is a need for accurate measurement for diagnosis specific to the trunk or thorax, the difference in shape should perhaps be considered.

Thorax rotation seem to be measure similarly with the two models, even though there are statistically significant points. These points and differences could be explained by how the spine moves differently throughout the vertebral column and that would register depending on if you measure from the thorax (IOR) or at the neck (Lundberg). The points would probably not be considered clinically significant, though, as they are very small when considering the whole curve.

Comparing the results to Leardini et.al. [8] it would seem that they have flipped their curves or coordinate systems, as they look similar, both in shape and angular value. No extra manipulation was done to the raw data in Visual3D, for neither IOR nor Lundberg, and as the other curves have the same pattern (IOR and Lundberg) one could assume that the size of the offset seen in trunk/thorax tilt is still correct.

As the IOR model have a thorax segment, instead of a full trunk, one could expect some difference in the trunk/thorax angles. Tilt mainly shows an offset, showing that both of the models measure the same motion-pattern, but presumably with different start-angles as the coordinate systems are centered in different parts of the spine. No visible pairing, as was seen in the pelvis tilt and rotation, was visible for either thorax/trunk plane. This is probably due to the difference in model definition. The shape of the obliquity is interesting as they are very similar but visibly different shape. IOR has a greater max-min angle while Lundberg has more distinct curvature (local min/max). If this difference is clinically relevant is hard to say as they describe a motion on different parts of the spine. This is important to have in mind when only examining the trunk mechanics.

5.2 Overall Model

The temporospatial parameters are very similar between models. This concludes that both models track the body segments as well as the kinetics very similarly. The difference that can be seen are probably due to that the models, in Visual3D, have a different threshold for defining the events so that they end up with different lengths. This difference is of a few frames but could be the reason to why symmetry 4.3b shows a visible, although small, difference. The models could therefore be assumed to measure very similarly.

The additional angles, moments and power briefly analysed in this report showed a good agreeability between the models, although no visible pairing was present like for pelvic tilt and rotation. A slight offset was seen in ankle flexion which at the moment is not explained.

The inter-subject difference is quite large (up to ± 8°) for several angles and overlap with the mean curve of the other marker model. Therefore it is difficult to say what is clinically significant as the results vary much between the subjects. What should be taken into account though is the shape of the curve as a the curve of a sick or injured patient differ from a healthy subjects curve. Some curves are visibly paired between models giving the appearance of a good fit of the models them being very similar.

The reason of differences between the models might not be that one is better at describing the body than the other. Determining which one is better at describing the trunk during walking is hard to say without having something to compare with, a true version of the skeletal movements. Both of the models can be describing a movement wrong, but do it in the same way, giving the impression that they are describing the true motion as both show the same thing. At the same time one model can be very close to the true motion, but without the true motion to compare with, it will be impossible to say which model is closest and therefore "the best". There has not been sufficient (none which the author know of) tests comparing the two trunk marker models to the golden standard; RSA. Some studies has been done to the Lundberg skin marker model, comparing it to RSA, but this has only been done with the lower extremities and therefore not much is known about how well the marker model is applied to the trunk.

Other variables that makes a model better than the other is the ease of use. The Lundberg skin marker model was designed to be quick and easy to use as it is often used on children. Children are prone to be very easily distracted and therefore quick to take off markers recently put on. An easy and quick model is therefore of high importance. Similarly, the IOR skin marker model for the lower body was also designed with children in mind [9] and a separate test with children would be needed to conclude the difference in ease of use. The Lundberg model includes 18 markers on the lower body (foot, shank, thigh and pelvis) and 8 markers on the trunk (including the pelvis). This in contrast to IOR with 22 markers on the lower body (foot, shank, thigh and pelvis) and 14 markers on the trunk (including the pelvis). The Lundberg model therefore has a simpler model, only looking at the number of markers used.

One should perhaps also consider the ease of which the anatomical landmarks can be found, where the markers should be placed upon, when comparing which model is easier. The IOR trunk model was created and modified from the previous standards to accommodate this where a spine-marker were placed at MAI which was considered easier to find rather than a specific vertebrae [8]. Qualisys also made a change to the IOR model where they changed the placement of the marker at the great trochanter and placed it further down the femur. This was a decision made with the motivation to make it easier for clinical use. A marker that high on the thigh requires very minimal clothing, and giving the patient the opportunity to wear more comfortable clothes can improve their ability to walk more normally during analysis. The IOR model also includes 6 static markers, only used under calibration of the model. These had a tendency to fall off as they were situated medially and the legs or feet would rub them off while walking. This was a cause of disturbance and distraction during the measurements, which could have been avoided either by removing the markers after the static measurements or by using pointers instead of markers, as described in the original protocol [9]. We chose to use physical markers as this is what the Qualisys protocol suggested.

6
Conclusion

The results from this thesis shows that trunk segment definition matter. The source of the differences lies in where the coordinate system origin and rotation center are situated. The trunk/thorax tilt showed an offset, but otherwise very similar curves. Trunk/thorax obliquity had different curve shape for the different models. Trunk-/thorax rotation did not show much difference apart from a few points that might be relevant. Even though a difference can clearly be seen, that does not always mean that one model is better than the other but rather that one must compare studies with caution if they use different models and the choice of a certain marker model depends on what is to be analyzed.

It is important to know the model you are working with not only from a practical point of view but also for a better understanding when diagnosing. Having a thoratic tilt of $-10°$ might be considered as an abnormal back bend to some clinicians but according to the marker model that angle describe a normal gait. Good knowledge about the marker model used is important, to be able to put the results in relation to a normal gait. It is especially important to have a good knowledge about a model if one would want to change one marker model to a new one.

This thesis could be used as a guide when comparing results from different articles using either of the marker models described here, to be able to compare the results in a better way. This will hopefully lead to better understanding and less confusion when seeing results that might look like it differs a lot from ones own, using a different model. As a great amount of data was collected, more than what is included in this report, there are also possibilities for future research for a more detailed analysis and on more angles.

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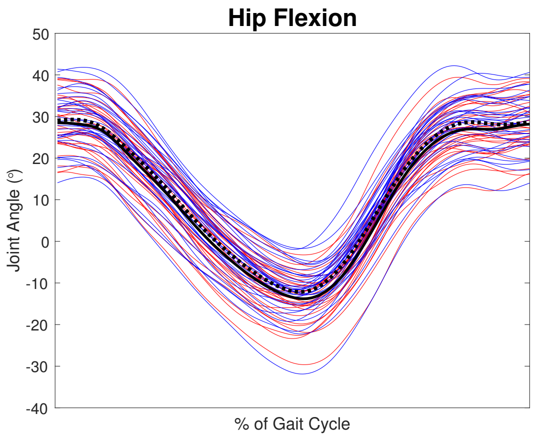
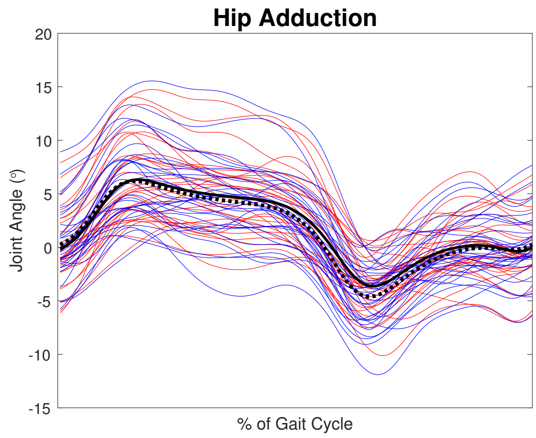
A

Appendix 1

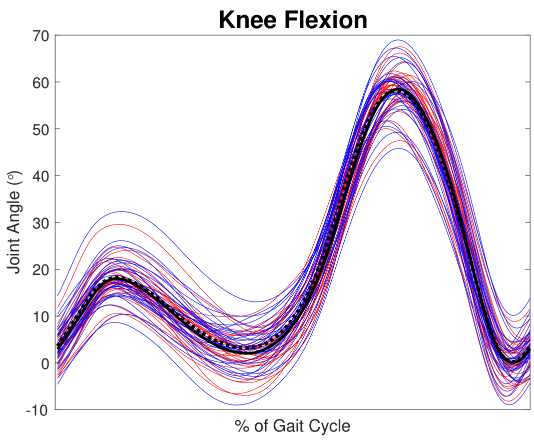
Additional angles, hip flexion and adduction, knee and ankle flexion, as well as moments and power for hip, knee and ankle. No clear difference can be seen in any figure, apart from a slight offset in ankle flexion, figure A.1d



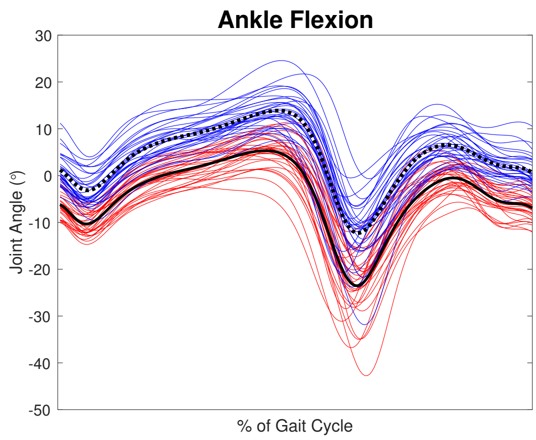
(a)



(b)

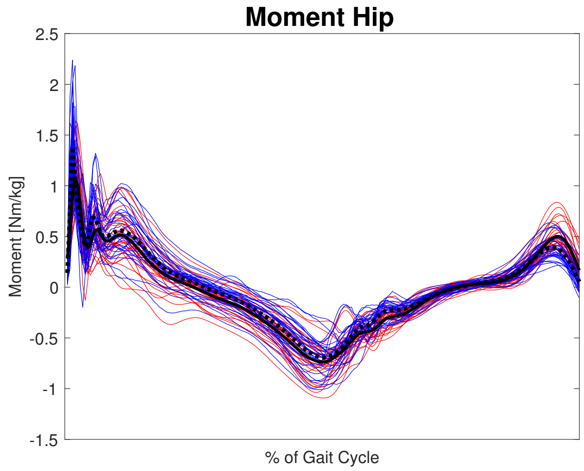


(c)

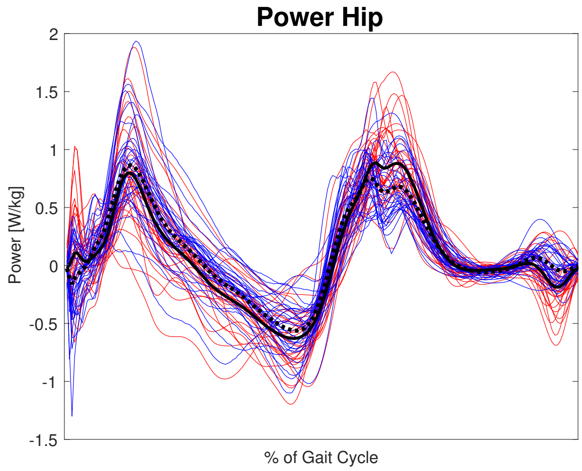


(d)

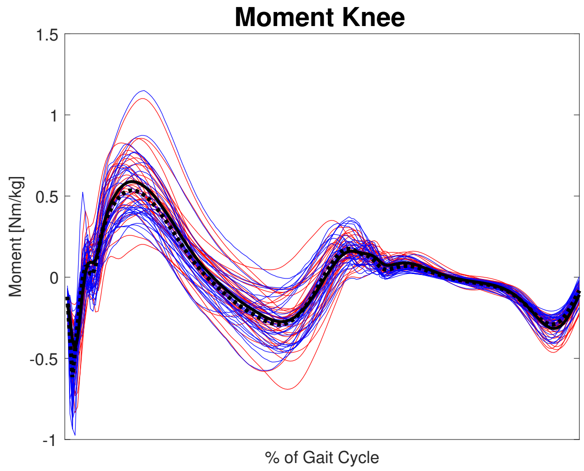
Figure A.1: Plots of the analysed angles. Figure a) shows hip flexion, b) hip adduction, c) knee flexion, d) ankle flexion. The red lines represent the IOR model with dashed line as the mean, the blue lines represent the Lundberg model with full line as the mean.



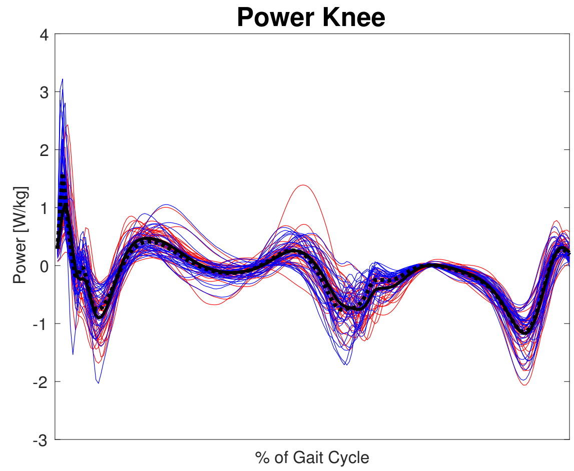
(a)



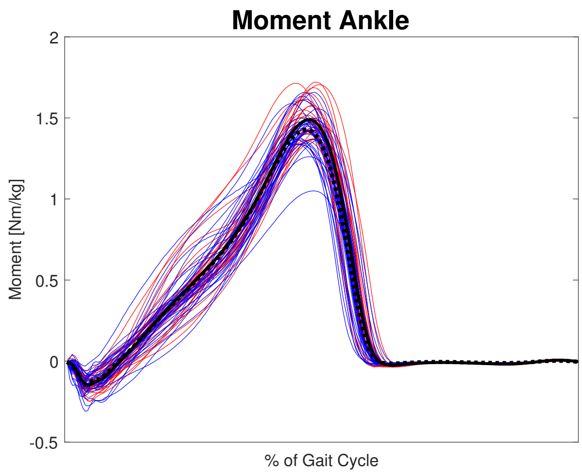
(b)



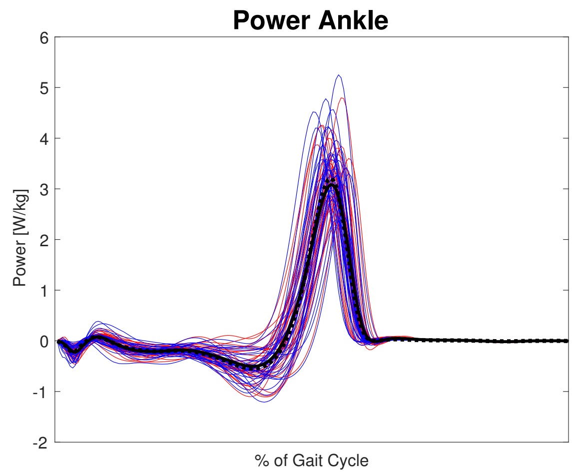
(c)



(d)



(e)



(f)

Figure A.2: The plots of moment and power for some joints. Figure a) shows hip moment, b) hip power, c) knee moment, d) knee power, e) ankle moment and f) ankle power. The red lines represent the IOR model with dashed line as the mean, the blue lines represent the Lundberg model with full line as the mean.

B

Appendix 2

The IOR, figure B.1, Lundberg, figure B.2, and hybrid, figure B.3, skin marker models with detailed description of marker placement and name. Abbreviations are described in section 2.3.2.1, 2.3.2.2 and 3.1.1 respectively.

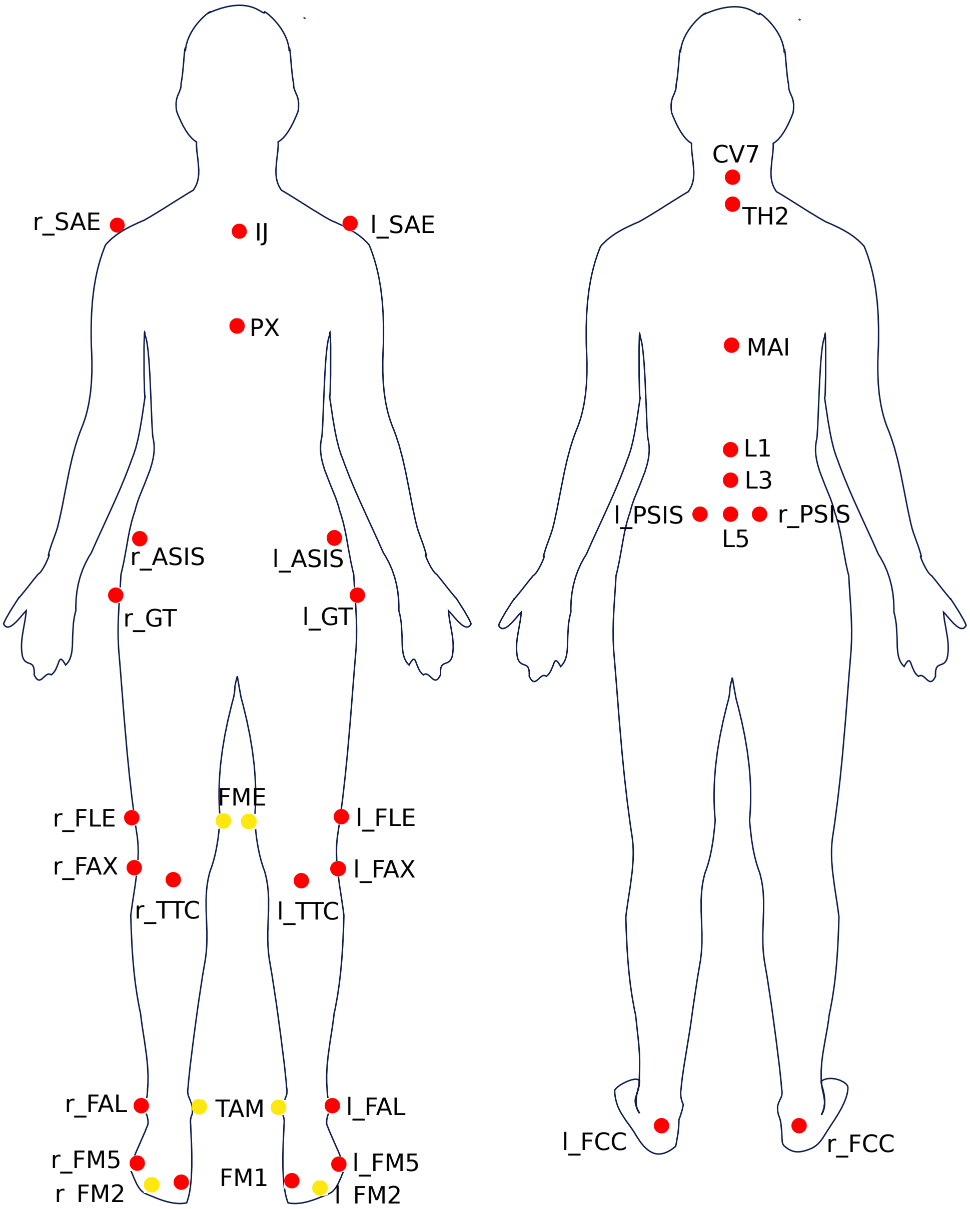


Figure B.1: The IOR skin marker model for trunk and lower body. Yellow markers are static markers.

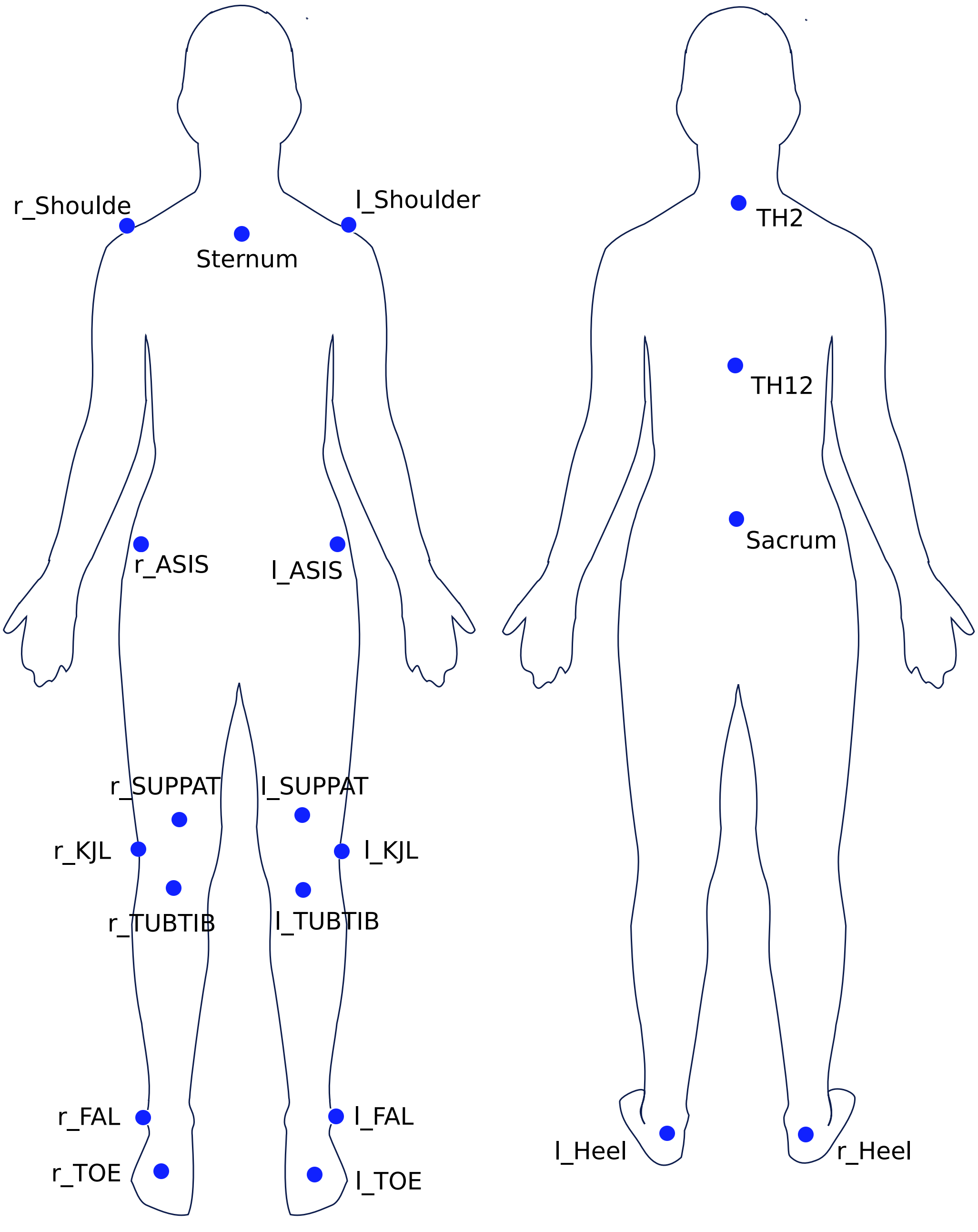


Figure B.2: The Lundberg skin marker model for trunk and lower body.

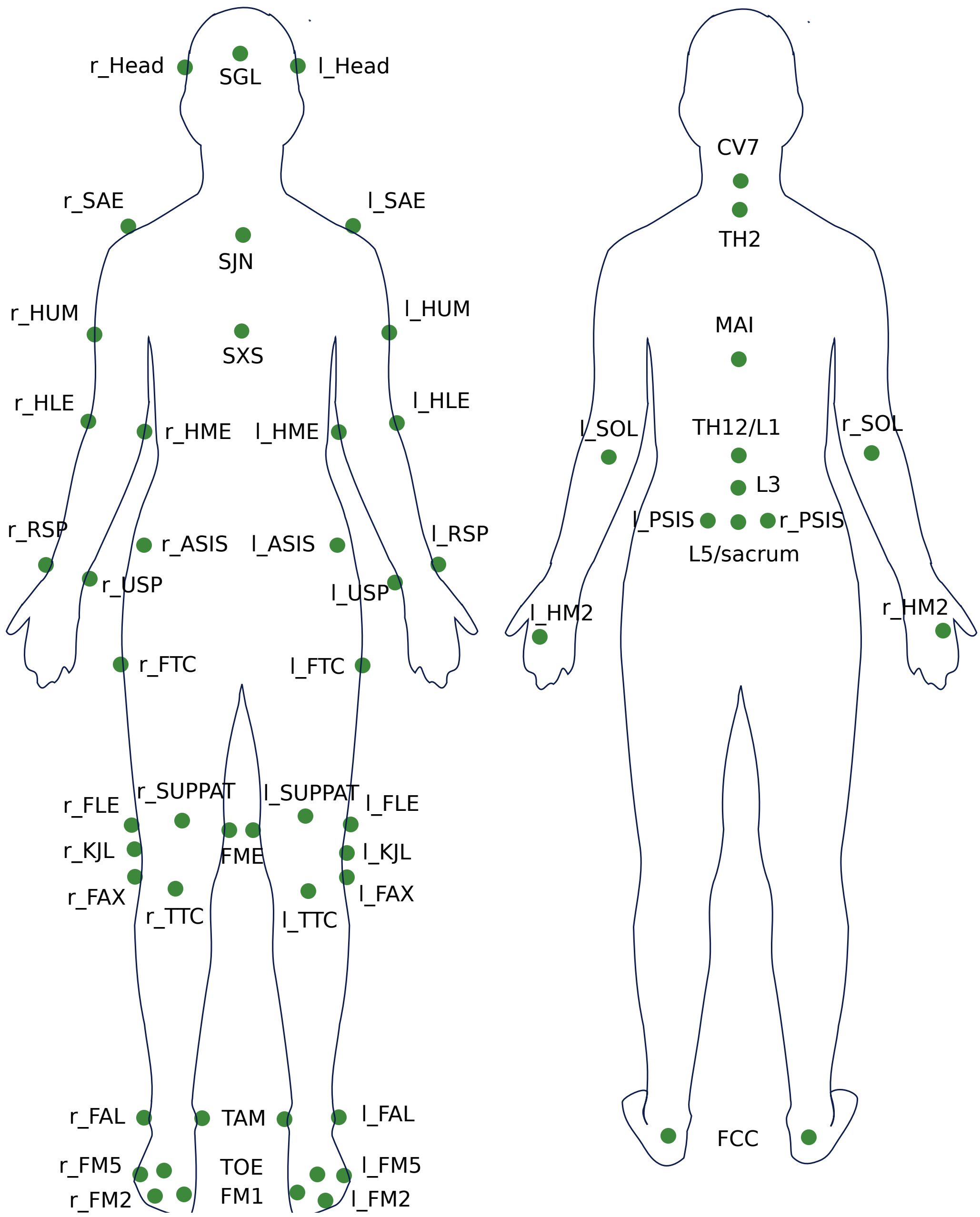


Figure B.3: The Hybrid skin marker model for a full body.