How does altering the foot progression angle affect lower limb kinetics, spatiotemporal and kinematic gait parameters when using a haptic feedback system?

A product for people with knee osteoarthritis

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How does altering the foot progression angle affect lower limb kinetics, spatiotemporal and kinematic gait parameters when using a haptic feedback system?

Thesis report

by

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to obtain the degree of Master of Science
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Preface

Looking back at my time as a student,I enjoyed all of it. First doing my bachelors Industrial Design, that followed with the master Biomedical Engineering. One of the best decisions I made, I really enjoyed this master and found my passion for this direction.

I also want to thank my supervisors, Jaap Harlaar, Mariska Wesseling and Erin Macri for all the help. Jaap with all his knowledge that was always very helpfull to continue with the thesis, especially at the beginning of the thesis when everything went different than expected. Also special thanks to Mariska, for every time she was available to videocall shortly after I mailed with yet another question. Also I'd like to thank Martin Schepers from Moveshelf for the information and help I got to be able to use their sensors. And Bram Bicknese from Elitac Wearables, who helped me to use their feedback system.

During the time I wrote my masters thesis I had great support from my family, friends and my roommates in Delft. Great thanks to the roommates to celebrate all the small steps we achieved and leaving supportive and loving notes for eachother. Thanks to my friends for helping me with excecuting my tests and collecting the needed data for this thesis!

Abbreviations

FPA	Foot Progression Angle
KAM	Knee Adduction Moment
pKAM	peak Knee Adduction Moment
KFM	Knee Flexion Moment
pKFM	peak Knee Flexion Moment
GRF	Ground Reaction Force
CoP	Center of Pressure
CoM	Center of Mass
NG	Normal Gait
TI5	Toe-in 5
TI15	Toe-in 15
TO5	Toe-out 5
TO15	Toe-out 15

Summary

Knee osteoarthritis is a common joint disease, affecting the knee joint. To help slow down the degeneration of cartilage, changing people's gait is a known solution. The most common modification is teaching people to walk toeing-in or toeing-out, changing their foot progression angle (FPA). However, it is still unclear what the effect is of changing the FPA on other gait parameters and lower joint kinetics. Changing the FPA, also changes gait parameters such as gait speed, step width, stride length, trunk lean, and medial thrust. It is hypothesized that lower joint kinetics are negatively affected when altering the FPA. This thesis focuses on the effect on the lower joint kinetics and on the gait parameters when changing the FPA.

Tests are done on healthy subjects with four FPA alterations besides normal gait, a small and large angle toeing-in and toeing-out. A haptic feedback device is used that contains vibrating motors located at the medial and lateral side of the calf to teach participants to walk in the desired angle. First participants are asked about the ease of use and comfort of the haptic feedback system. Second, the knee adduction moment (KAM) and knee flexion moment (KFM) are measured for each participant to evaluate the effect of the different FPA's. Third, the moments in the lower joints, hip and ankle, are measured to research the effect of different FPA's on the loading within these joints. This load is measured at peak value and as area under the graph. Lastly, there is researched what gait parameters participants alter when changing the FPA. The thesis mainly focuses on the effect on the lower joint kinetics since literature still shows a gap here.

The haptic feedback resulted comfortable for most participants, the ease to achieve a high amount of correct steps within the asked FPA appeared more difficult. Changing the FPA to reduce the KAM, showed for the participants different angles that maximally reduces the KAM. Highlighting the importance of a personalized approach. The hip adduction moment and ankle moment both increase overall for the participants. While the hip rotation and flexion moment show a mean reduction. Making it important to focus most on the hip adduction moment and ankle moment, and how to lower these increases in moment. Otherwise this could result in hip osteoarthritis. Different FPA's also change the impact of the gait parameters for the participants. Indicating participants to change their entire posture when adapting different angles. Resulting more aspects to focus on when learning participants to walk differently.

To conclude, changes in the FPA have effect on the KAM, gait parameters, and on the lower joint kinetics. The reduction on KAM differs per participant, indicating a personalized approach. Gait parameters change when applying FPA's, mainly gait speed, stride length and step width change for most participants. Measurements on the lower joint kinetics show interesting insights on the effect of changing the FPA. Highlighting the hip adduction moment and ankle moment to focus on to prevent possible excessive load and damage.

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Part I

Introduction

01

1. Background

1.1 Knee osteoarthritis

The most common joint disease in elderly is knee osteoarthritis (KOA), affecting especially persons aged 50 and above. Additionally, females are at a higher risk relative to males. (Helmick et al., 2008) The knee is the weight bearing joint affected by abnormal loading patterns resulting in KOA. (Hunt & Takacs, 2014) The knee joint is composed of three compartments; the medial compartment, the lateral compartment and the patella-femoral joint.

The pathogenesis of KOA manifests as matrix degeneration within the knee joint. One contributory factor is obesity, given a direct correlation with increased biomechanical stress exerted upon the knee joint. Every additional 0.45 kg of body weight results in an extra 0.9 to 1.8 kg of excessive load on the knee joint, thereby amplifying the joint's mechanical burden. (Lespasio et al., 2017) Knee osteoarthritis is characterized by articular wear and tear in the joint, culminating in cartilage loss and consequent bone-to-bone contact during physical exercise. (figure 1)

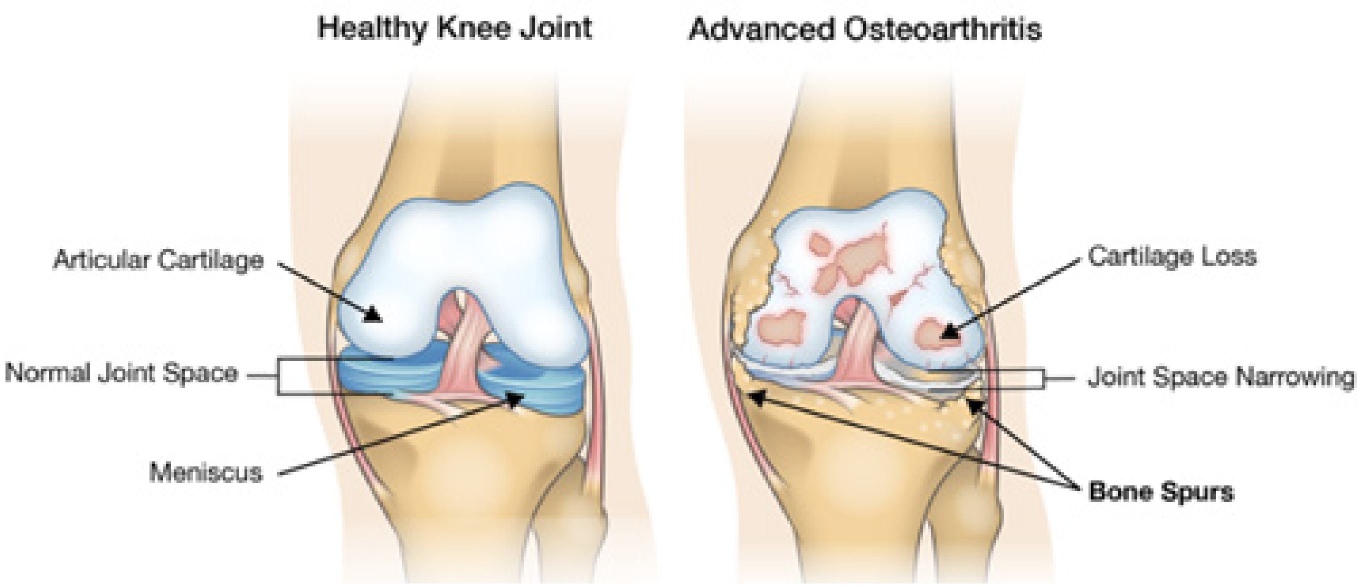

Figure 1: Forming of KOA
The difference between a healthy knee and a knee affected by KOA, it shows cartilage degeneration, joint space narrowing, and bone spurs

Symptoms that are experienced are activity-induced knee pain, joint stiffness, swelling or pain after prolonged resting, and an overall increase of pain over time. When osteoarthritis advances beyond a certain threshold of development, increasing the pain and decreasing the quality of daily life, surgical intervention becomes the last solution. (Mancuso et al., 1996)

Most common is medial KOA, where the medial compartment is most affected, the medial compartment is ten times more often affected than the lateral compartment. Other possibilities are that multiple compartments are affected by OA. (McCormack et al., 2021)

Literature shows the pivotal role of exercise in retarding the degradation of the extracellular matrix, thereby delaying the progression of OA degeneration. One study (Kong et al., 2022) examens the different gait adaptations that individuals with KOA can undertake to influence the load on their knees. The dynamic load on the knee joint has shown to influence the progression of OA. (Schipplein & Andriacchi, 1991) Forces to focus on within the knee are the knee adduction moment (KAM) and the knee flexion moment (KFM). These moments influence the load on the knee joint. The KAM is well known to focus on for people with KOA, the KFM is less researched. Even though KFM is an important moment in the knee loading as well. (Walter et al., 2010) The KAM increases the load in the medial compartment, while the KFM exerts more load on the medial and lateral compartment of the knee. (Chehab et al., 2014) Highlighting the importance to include both moments in the knee within this research.

1.2 KAM

The KAM quantifies the external torque acting around the knee joint in the frontal plane. This moment describes the load distribution across the knee joint between the medial and lateral compartments. KAM is determined by the ground reaction force (GRF) and its lever arm. The KAM contains two distinct peak moments in the gait cycle, the first peak transpires during the early stance phase, emphasizing the rolling motion of the foot until the entire plantar surface is on the ground. The second peak appears during the second half or late stance phase, focusing on pushing the plantar surface of the foot of the ground on the toes. (Farrokhi et al., 2013) (Schelhaas et al., 2022) (figure 2) An altered foot position reduces the KAM through the mechanism of reducing the moment arm length of the net GRF vector with respect to the knee joint center.

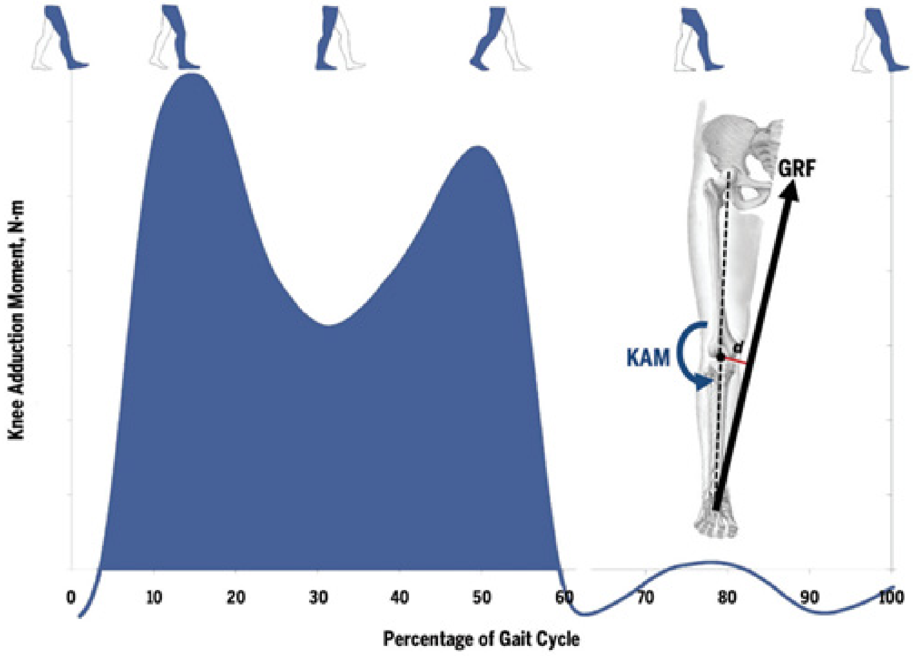

Figure 2: the gait cycle
The gait cycle with the two peaks during KAM and where they appear during the gait cycle, the 1st peak being during the early stance phase during planting the surface of the foot on the ground, the 2nd peak being during the late stance phase focusing on pushing the plantar surface of the foot of the ground (Farrokhi et al., 2013)

A larger KAM is associated with greater disease severity and pain, since it measures the compartment loading during walking. (Farrokhi et al., 2013, Foroughi et al., 2009) The KAM measures load at one moment and does not include the duration of loading, this duration of loading can be influenced by walking speed. The KAM reflects the distribution and magnitude of the load transferred through the medial versus the lateral compartment of the tibiofemoral joint. (Foroughi et al., 2009) Various gait adaptations that influence the KAM are walking speed, stance width, stride length, medial thrust, and foot progression angle (FPA). Literature shows FPA (toeing-in and toeing-out) a widely recognized strategy to reduce the KAM. (Simic et al., 2013)

1.3 KFM

The Knee Flexion Moment (KFM) is expected to be influenced by change in KAM. Most literature only focuses on the effects of the KAM when altering gait. However, both moments influence the load in the knee joint. (A. H. Chang et al., 2015) Additionally, the KAM and KFM are defined in orthogonal planes, and exert load on different compartments of the knee. (Chehab et al., 2014) Other literature also emphasizes the negative effect of an increase in KFM on the load on the medial side of the knee. (Creaby, 2015) The peak value of the KFM is used for the analyses, (Chehab et al., 2014) the area under the curve of the KFM can be taken to research the increased joint compression. Besides, it is found that while the KAM decreases, at the same time the KFM can increase. This affects the knee joint, since the goal is to decrease both moments. Highlighting the importance to examine both moments for maximal information about the exact load in the knee. (Walter et al., 2010) An increase of KFM over five years keeps increasing the medial load in the knee. (Chehab et al., 2014)
The KFM contains two peaks around the same time as the peaks for KAM. The first peak of KFM is opposite direction (more negative) compared to KAM, while the second peak KFM is the same direction as KAM, both positive direction, figure 3. It has been researched that KAM accounted for 63% of the forces on the knee. Additionally, KAM and KFM were found not to be correlated, proving that both moments are unique and both important to research for peak loading. (Manal et al., 2015)

Changing the FPA affects the KFM peak. The goal is not only to decrease the KAM, but also the KFM to release the knee joint from the additional forces. Other gait parameters as step width , trunk sway and gait speed also affect the KFM peak. (Favre et al., 2016) The current literature shows different outcomes for the effect of changing the FPA on the KFM. One literature showed that toe-out gait reduces the KFM (Favre et al., 2016), conversely other research found that toe-out gait increases the KFM. (Schache et al., 2008) (Jenkyn et al., 2008) This shows that there are still questions concerning the exact influence of the FPA on the KFM, making it important to include this in this research.

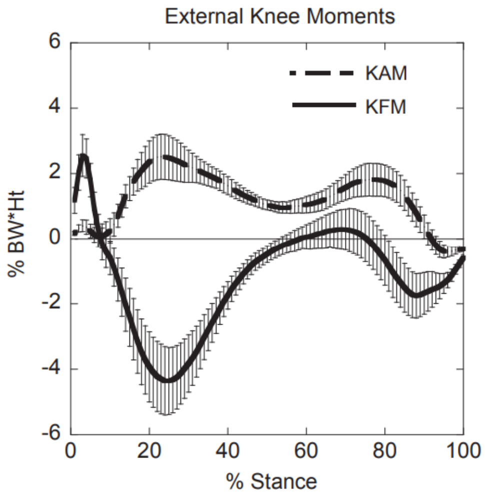

Figure 3: Relation KAM and KFM
This graph shows the relation between KAM and KFM during stance phase (Manal et al., 2015)

1.4 FPA

The FPA is the angle of the foot in the horizontal plane relative to the direction of walking. (Richards et al., 2018) (Karatsidis et al., 2018) This angle is a critical determinant influencing the KAM. (Schelhaas et al., 2022) The FPA is affected by rotating the foot inwards or outwards; toe-in or toe-out. (figure 4) The first peak within the gait cycle is affected by toeing-in and the second peak is affected by toeing-out. Changing the FPA is a widely recognized strategy to influence the KAM.However, literature shows different ranges of FPA. Participants can be asked to walk between five to thirdy degrees. (Shull et al., 2015) (Booij et al., 2020) (Seagers et al., 2022a) (Simic et al., 2013) Different FPA are applicable for the participants, resulting in always implementing multiple angles within each research to analyze the differences.

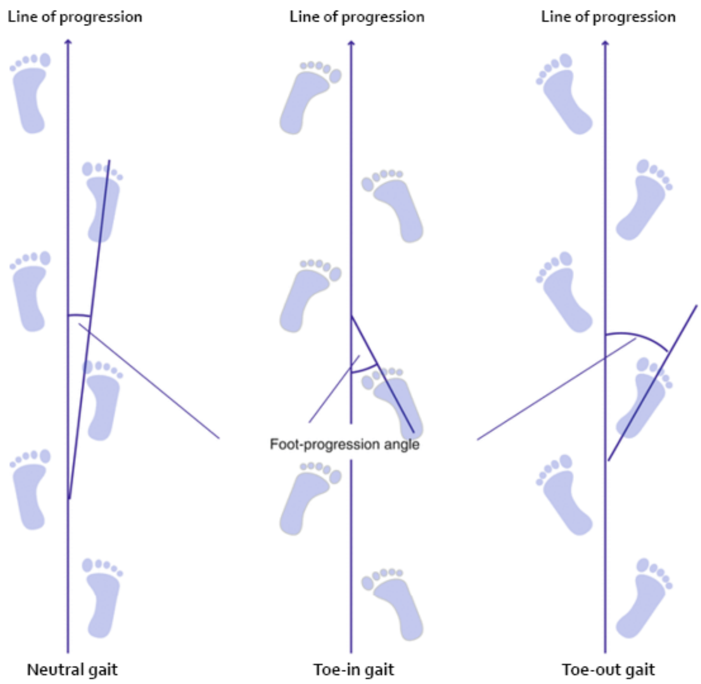

Figure 4: FPA
The figure shows the difference between neutral gait (normal gait), toe-in gait, and toe-out gait

In current research there is not one FPA that maximally reduces the KAM and KFM for all participants. Implementing personalized advise can increase the maximal decrease in these moments. However. Few literature includes the research to personalized angles. Every individual walks differently and it is necessary to measure their normal foot postures to be able to give a fitted personalized approach. (Qiu et al., 2020). Individuals with a more posterior lesion within the medial compartment of the knee are likely to benefit more from toe-in gait training protocols aimed at a reduction of the first peak KAM. Conversely, those with lesions of a more distal nature may find toe-out strategies more advantageous, aimed at reducing the second peak KAM. However, this is an expectation, sadly not fitted for everyone. Reasoning to analyze everybody's gait pattern compared to their normal way of walking to find the best fitted change in gait and create a personalized advise.

1.5 Spatiotemporal and kinematic gait parameters

Changing the FPA is expected to reduce the KAM. However, this alteration in gait can also affect other paramters, such as gait speed, step width, stride length, trunk lean and medial thrust. Subsequently these changes in gait parameters can increase the KAM or KFM, what is not wanted. The consequences remain understudied in the literature, emphasizing the importance of investigating whether individuals with KOA, when adjusting their FPA for knee pain relief, inadvertently expose themselves to additional pain and risks.

There are two types of parameters; spatiotemporal parameters and kinematic parameters. Spatiotemporal parameters include gait speed, stride length, and step width. Kinematic parameters include trunk lean, and medial thrust gait.

The gait speed influences the KAM. A higher gait speed increases the first peak of the KAM, while a lower gait speed decreases the KAM. When comparing a high to a low gait speed, the higher gait speed increases the KAM more, since it increases the peak knee joint loading. (Khan et al., 2017) (Farrokhi et al., 2013) (Lerner et al., 2014)

The stride length is the distance between the calcaneus at the midstance to the next midstance index (figure 5). (Bennour et al., 2018) Walking with a shorter stride length while maintaining gait speed decreases the KAM in healthy participants. (Ulrich et al., 2023) Additionally, other literature shows a shorter stride length does not only decrease the KAM, but also decreases the KFM. (Edd et al., 2020)

Step width (figure 5) is the distance between both ankle joint centers. (Favre et al., 2016) A wider step width reduces the peak KAM significantly. Besides it shows a displacement of the center of mass (CoM), subsequently this can shorter the moment arm of the knee joint and thus decreasing the KAM. (Anderson et al., 2018) Combining toe-in and wider step width, decreases the 1st pKAM. Conversely, when only applying toe-in the 1st pKAM is reduced less. Looking at the 2nd pKAM, toe-in in combination with a wider step width has no to little influence on the KAM. (Bennett et al., 2017) However, a wider step width can increase the KFM. (Edd et al., 2020)

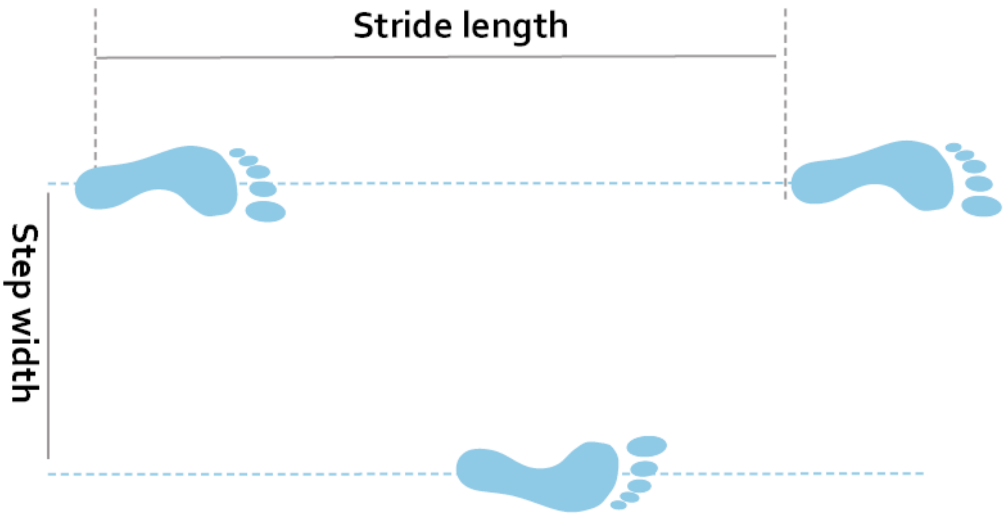

Figure 5: Stride length and step width
The definitions of stride length and step width are shown, stride length is the distance between the calcaneus of the right foot when it is flat on the ground again, step width is the distance between the left and right calcaneus

Trunk lean also influences the KAM and the CoM. This moves the knee closer to the GRF vector, reducing the frontal plane moment arm and therefore the KAM. (Anderson et al., 2018) Increasing the trunk lean (10±5°), towards the investigated knee, literature shows an average reduction in KAM of 65%. Additionally, it shows a reduction in the first peak adduction moment at the hip. (Mündermann et al., 2008) Literature that focuses on the trunk lean, shows an increase of 7° to 17°. (Shull et al., 2011) Other literature shows a natural trunk lean of 2.5 ± 2.0° to a lateral trunk lean of 7.7 ± 2.7°. (Anderson et al., 2018) Increasing trunk lean, can decrease the KFM. (Lindsey et al., 2021)

Lastly, an increase in medial thrust brings the stance leg knee toward the midline of the body. (Fregly et al., 2009) It is shown that medial thrust gait shifts part of the contact load of the knee lateral, and decreases slightly the total contact force. The effect of medial thrust can be in a slightly increased hip rotation, and slightly increased leg flexion. Literature also shows that after walking 1,5 years with increased medial thrust gait this reduces the pain in the knee without problems to other lower joints. (Fregly et al., 2007) Additional literature indicates medial thrust gait significant reducing the KAM in the first peak, and reducing the hip flexion moment. (Bokaeian et al., 2021) However, increasing medial thrust, combined with increasing toe-in angle, possibly increases the peak KFM. Which may influence reducing the pKAM negatively. (Lindsey et al., 2021) As is mentioned above, the gait parameters are widely influenced by changing the FPA. Making this important parameters to include within this research.

1.6 Lower limb kinetics

Although toeing-in and toeing-out can positively influence the KAM and KFM, adverse effects on other lower joints can appear when changing the FPA. Current research only focuses on the effect on the knee when changing the FPA, not on the hip or ankle. Literature (Lindsey et al., 2021) indicates a potential increase in hip rotation when increasing the toe-in gait. Potentially increasing mechanical demand on the soft tissues around the hip. (Seagers et al., 2022a) Additionally, individuals with KOA are noted to shift their load-bearing from their knee to their ankle to lower the pain and load on their knee. (Zeni & Higginson, 2011) Other literature indicates changes in the orientation of the femur at the hip joint and/or the tibia at the ankle joint, what repositions the knee joint center closer to the GRF vector and thus reduces the external KAM lever arm. (Farrokhi et al., 2013) Current literature shows little and different evidence related to the influence of FPA on the hip and ankle joint. One literature shows on average an increase in hip adduction moment. (Foroughi et al., 2011) Conversely, other literature resulted on average in no increase in hip loading, on individual data increases and decreases in hip moments were found. (Seagers et al., 2022a)

Hip flexion is movement in the sagittal plane, hip adduction is movement in the frontal plane, and the hip rotation is movement in the horizontal plane. When the hip moment increases, this will increase mechanical demand on the soft tissue around the hip, and it alters the compressive loading resulting in cartilage damage. (Mündermann et al., 2005) For the ankle,literature shows that the ankle inversion moment occurs more in the second half of the stance phase then the first half, so during the second peak. (Mündermann et al., 2005) Expecting to see most effect of the ankle moment during the second peak of the KAM (pKAM).

2. KneeWear product description

Elitac Wearables and Moveshelf are developing a wearable device for individuals with KOA. This device will teach participants to walk differently by toeing-in or toeing-out. This gait adaptation changes the FPA and is expected to decrease the KAM. This device consists of two sensors and two applications.

The sensor of Elitac Wearables is worn on the participant's ankle (figure 6), providing vibrational feedback. This feedback is applied with each step to let the participant know whether an adjustment in foot orientation is required. The absence of feedback signals that the foot is aligned with the desired angle. This sensor is controlled with the Elitac Wearables application.

The second sensor, provided by Moveshelf, measures the FPA. This sensor is called the Xsens DOT sensor, this sensor is worn on the outside of the foot (figure 6), measuring the angle of the foot of the participant (toeing-in or toeing-out). The Xsens DOT sensor measures the roll, pitch and heading of the foot. Roll represents the rotation around the y-axis, pitch denotes the angle around the x-axis, and heading reflects the angle around the z-axis (figure 7). In this case the z-axis is used to measure the FPA and is zero when the foot aligns with the walking direction.

Figure 6: Fixture sensors
Fixture of the sensor from Moveshelf (around the foot), and the sensor from Elitac Wearables (around the ankle)

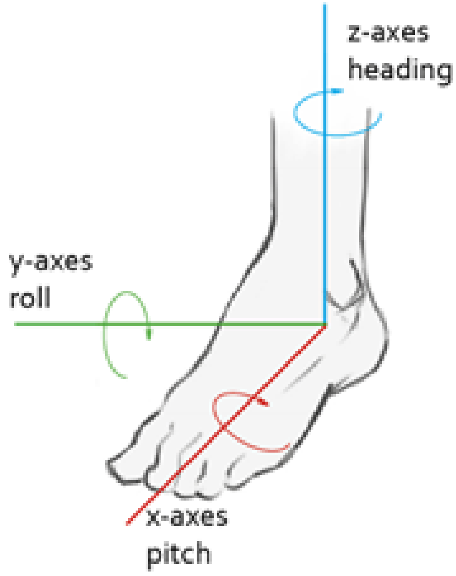

Figure 7: Directions Xsens DOT sensor
Clarification of the directions of the Xsens DOT sensor, roll, pitch, and heading

Activation of the sensors involves connection to the applications, followed by determining the walking direction by maintaining the foot still for a few seconds. When the direction of walking is determined the participant can start walking. The walking direction is changed by momentarily standing still for a few seconds and recalibrating. During walking in one direction no problems will occur with accidentally changing the direction of walking since standing still for a certain amount of time is needed before the walking direction is measured again.

2.1 Applications of sensors

Both sensors are connected to an application. The Moveshelf application receives the angle the participant is walking in from the Xsens DOT sensor, this value is communicated to the application of Elitac Wearables. The application of Elitac Wearables sends a message to the motors around the ankle that control the feedback, to teach the participant to walk in the desired angle. These vibrations teach the user to walk with the desired FPA, when the participant walks in the required FPA, no vibrations are given by these moters. (figure 8)

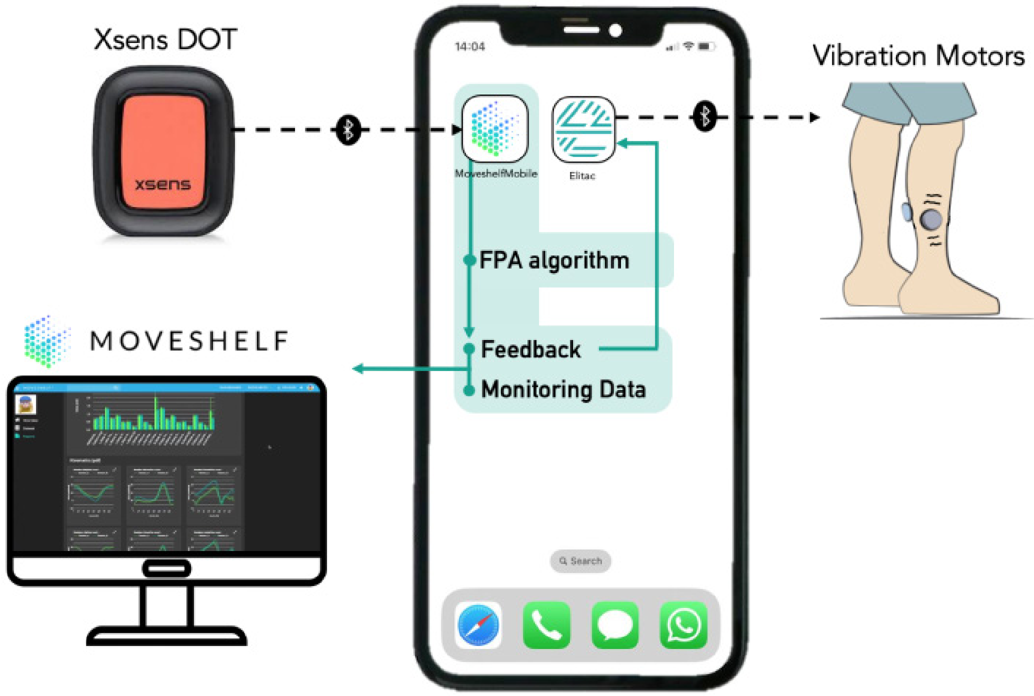

Figure 8: KneeWear product
How the KneeWear product works from Elitac Wearables and Moveshelf. First the Xsens DOT sensor sends information about the FPA to the application of Moveshelf. This application is in contact with the applications of Elitac Wearables, what in its turn gives information to the motors of Elitac Wearables that are located on the calf [Floor Heijs, 2023]

The current challenge with the KneeWear product revolves around the user responses to the haptic feedback system. Making it interesting to research users' ease of understanding the haptic feedback system; the comfort of the feedback, how quickly they can reach the desired FPA, and for how many steps participants are able to walk in the desired FPA.

2.2 Haptic feedback

Other used feedback, besides vibrations, within literature is audio and visual feedback. Mostly used in research is visual feedback, or a combination of feedback types.(Simic et al., 2013) (Karatsidis et al., 2018) However, this visual feedback is currently only applicable in lab bounded environments.
The benefit of implementing haptic feedback is that the device is wearable outside the lab environment. This way the participants can practice easily at home or implement it in daily life when the product is developed for this purpose. One literature already focuses on implementing a haptic feedback system. Here the feedback system is incorporated into the shoe sole and the vibration motors are applied at the inner surface of the shoe. Participants walked two minutes in the asked FPA and were able to take average 80% of their steps within the asked FPA. Showing the possibility of haptic feedback to succeed. Additionally, they added multitasking in combination to the feedback within the research. This did not influence the amount of good steps within the asked FPA. Highlighting the possibility of applying haptic feedback in daily life. (Shull et al., 2021)

3. Research questions

The following main research question was formulated based on the literature review and research objective:

'How does altering the foot progression angle affect lower limb kinetics, spatiotemporal and kinematic gait parameters when using a haptic feedback system?'

This main research question is answered using multiple sub-research questions. The following sub-research questions are used to answer the main question:

1. How do FPA adaptations impact lower limb kinetics, and other parameters?

What is the effect of changing the FPA on spatiotemporal and kinematic gait parameters
What is the effect of changing the FPA on lower limb kinetics

2. How does modifying the FPA to different angles affect the KAM?

3. How do participants perceive the usability and comfort of the haptic feedback system?

3.1 Research hypothesis

The feedback system is expected to be comfortable for most participants, since healthy participants are included probably no pain wil occur in joints. Regarding different FPAs, it is expected that participants exhibit individual preferences for an optimal FPA. The FPA will hopefully decrease the KAM for all participants, but the prefered angle will differ between participants. The KFM is expected to sometimes decrease alongside a reduction in KAM, and sometimes increase when the KAM decreases.
It is hypothesized that changing the FPA will affect the lower limb kinetics and the gait parameters. Especially when applying the larger FPA the effects are expected to increase the KAM more since the gait change is more compared to normal walking. For the lower joint kinetics the expectation is that an increase in load will appear, as participants change their gait and rotate their ankle and knee joint, what subsequently will alter loads in the hip and ankle joint. And increase loads in these joints that are not wanted.

Part II
Materials & Methods

02

4. Introduction to methods

The measurements are conducted at the motion lab at TU Delft, which is equipped with 12 motion capture cameras and two video cameras used for monitoring participant movements. Reflective markers are placed on anatomical landmarks of the participants to facilitate the capture of joint movements. The measurement of the GRF uses force plates, and the lab is equipped with five KISTLER force plates.

During the measurements, participants are instructed to walk back and forth. This enables the analysis of the participants' gait cycle. Figure 9 illustrates the gait cycle, consisting of a single step. The part that is used for the analysis is the stance phase (dashed yellow block).

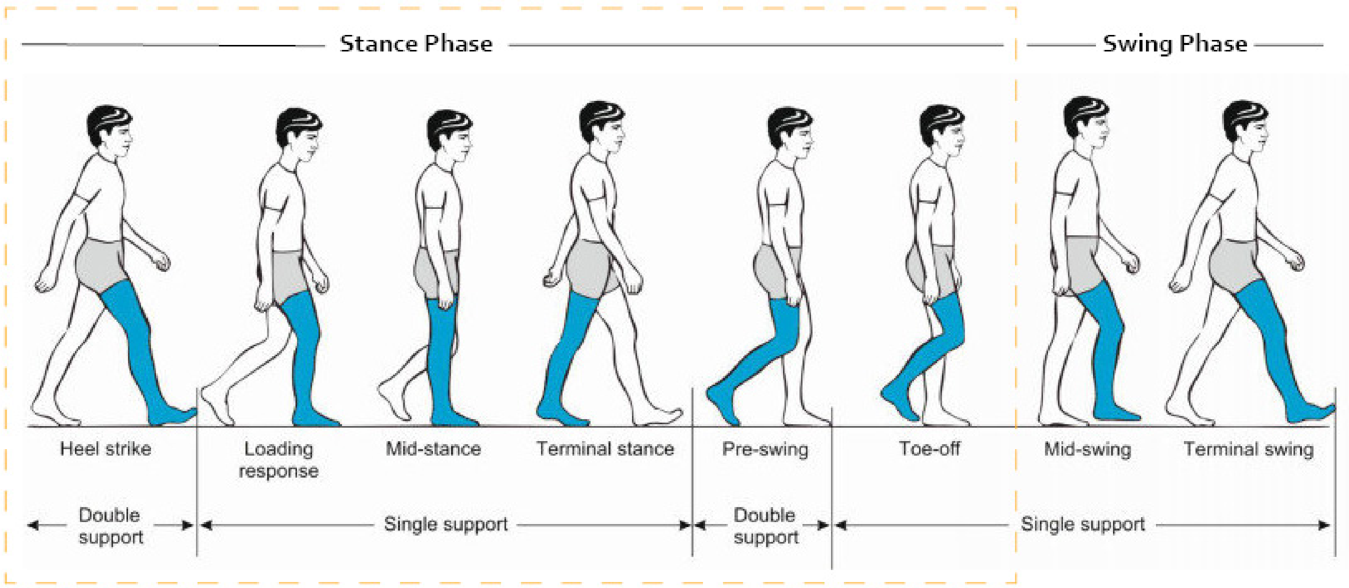

Figure 9: Gait cycle
One complete gait cycle, here the participant takes a step with both feet to complete one gait cycle, the part in the grey box is the part that is used to make the graphs in the result part and analyze the moments

The methods section describes the steps for the measurements, divided in the following parts: preparation, motion test, final tests, calculations, and the analysis. (figure 10)

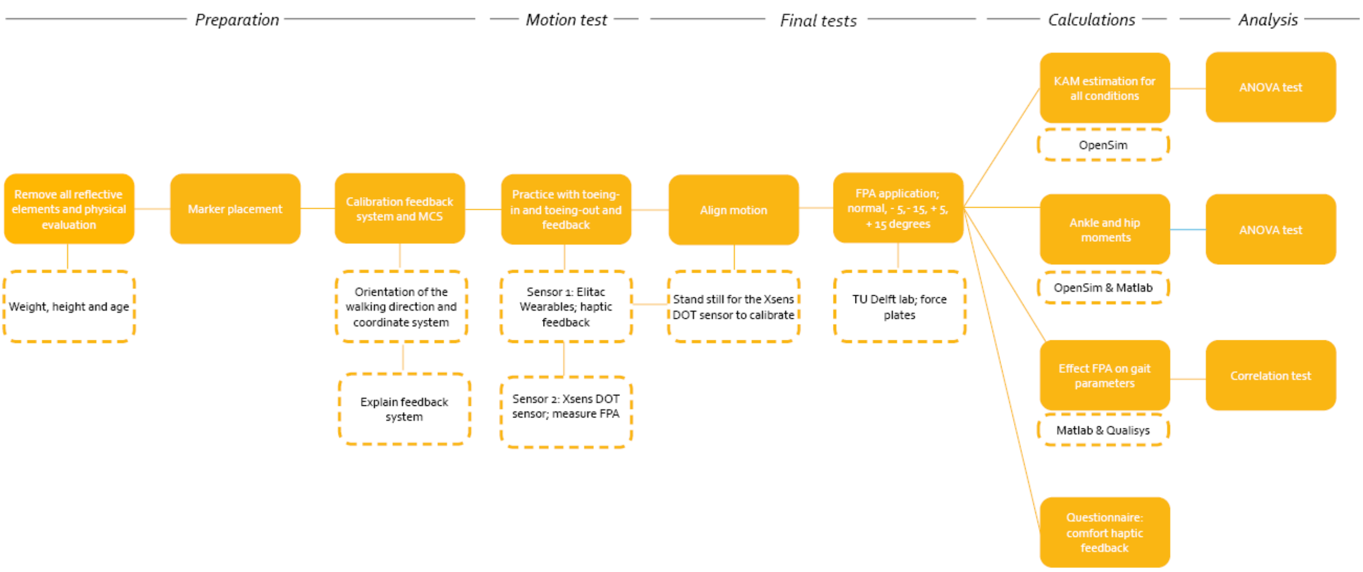

Figure 10: Overview measurements
Overview of the test-plan with the different steps and options: preparation, motion test, final tests, calculations, and analysis

4.1 Preparation

This research focuses on testing healthy participants, with a total of 20 healthy individuals participating, comprising 4 men and 16 women. Prior to the experiment, the test plan is approved by the Human Research Committee (HREC) of the Technical University of Delft. Participants were required to confirm there are no injuries to any joints at the time of testing. Besides they are asked to sign an informed consent before taking part in the experiment, this file is added to appendix A.

4.1.1 Lab preparation

Participants are instructed to walk back and forth over strategically positioned force plates and extra plates on the extremities to form a catwalk, figure 11. These force plates are located to capture the participant stepping once on each plate with one foot. The force plates enable measurements of the GRF and the CoP, to eventually calculate the KAM and KFM. The use of three force plates allows for multiple data points, enabling comparisons for usable data.

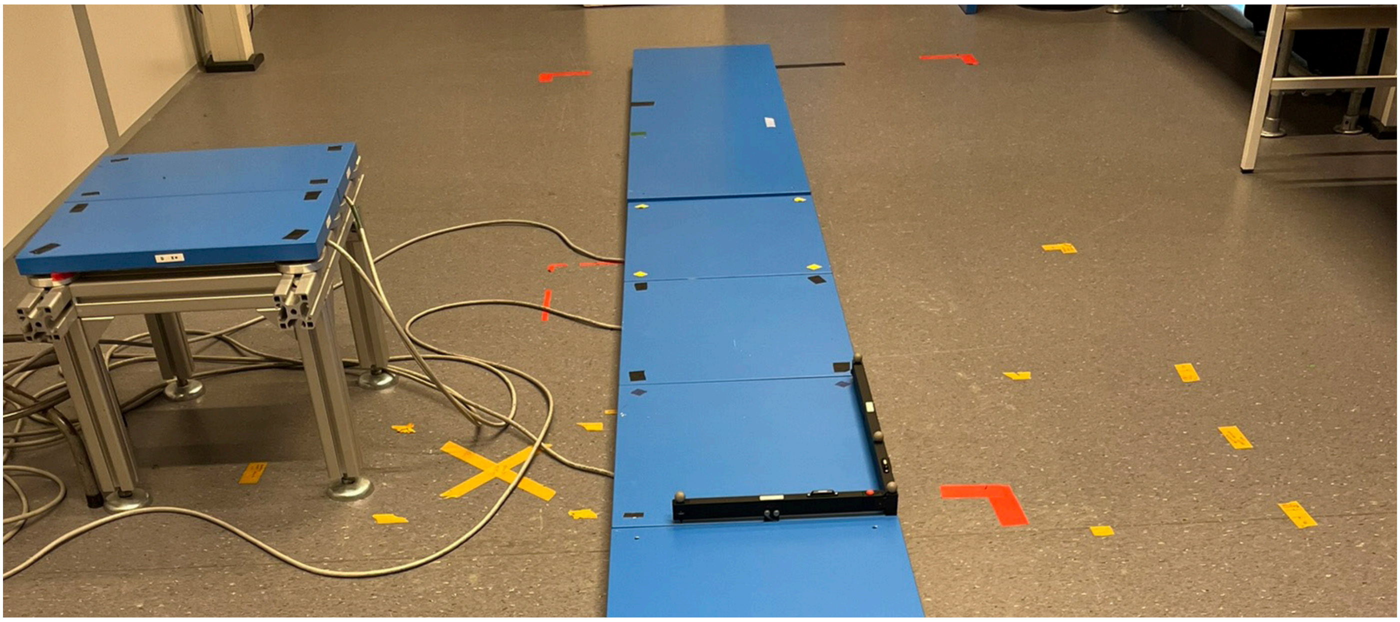

Figure 11: Set-up testlab
Test set-up in the Biomechanical lab at TU Delft, in the middle there are three force plates located, on the two extremities there are extra plates to keep the same height. Here are no force plates integrated

4.1.2 Marker placement

Markers are placed on the participants' anatomical landmarks to obtain the data for the measurements. (Cappozzo et al., 1995) The markers are placed on the foot, ankle, knee, pelvis, and shoulders. For the foot the markers are placed on the 1st and 5th metatarsal head (VM and FM), and on the calcaneus (CA). For the ankle two markers are placed on the medial and lateral malleoli (LM and MM). The knee has markers on the head of the fibula (HF), the tibial tuberosity (TT), and two markers on the medial and lateral epicondyle (ME and LE). For the hip the markers are placed on the anterior and posterior superior iliac spine (ASIS and PSIS), and on the sacrum. On the shoulders the markers are placed on the acromion on each side. One marker is placed on T1, one on T10, and the last marker is placed on the juglar notch, resulting in the usage of 28 markers. (figure 12) Lastly clusters are placed on the upper and lower legs of the participants. These clusters are included to be able to do measurements in different software. This way multiple options are possible, the right leg has two clusters since this is the leg that is examined. Some markers are placed on the participant, but were not necessary for data extraction. It was still included within these test to keep the options open for software use.

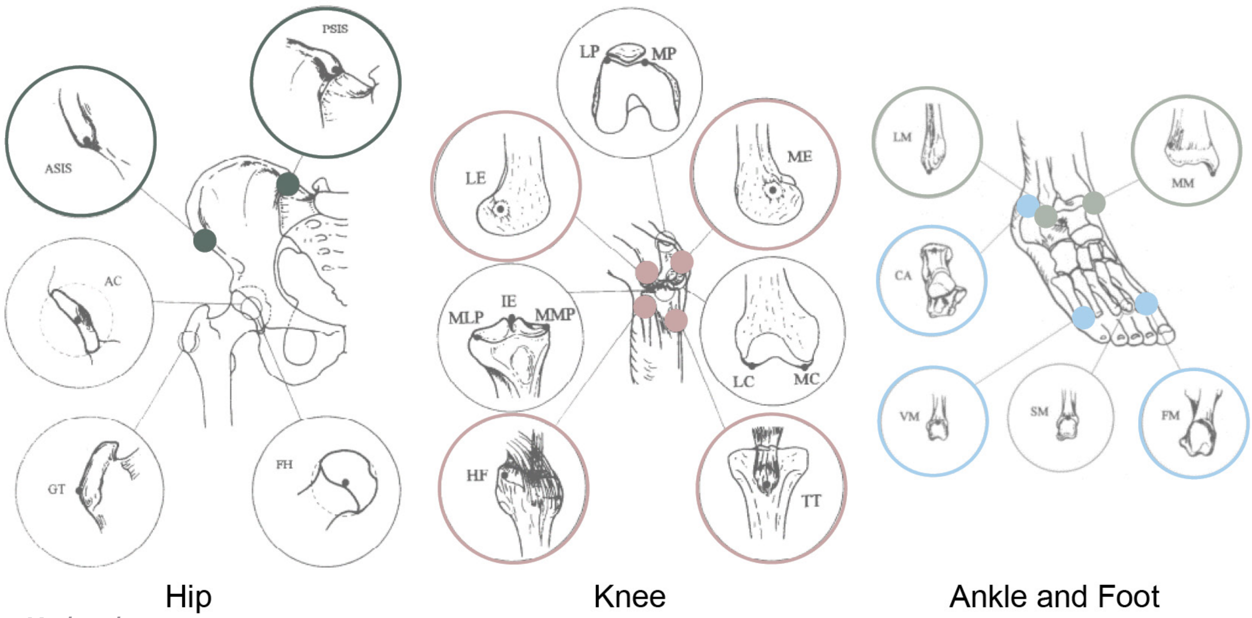

Figure 12: Marker placement
Location of marker placement on anatomical landmarks; the hip has markers on the ASIS and PSIS, the knee has markers on the HF, TT, ME, and LE, for the ankle the markers are on the LM and MM, and the foot has markers on the FM, VM, and CA.

4.1.3 Calibration

Prior to the measurements, a static calibration is done. Participants are instructed to maintain a stationary stance on one of the force plates for a few seconds, figure 13 and figure 14. Subsequently, the participant is asked to move the limbs while staying on one force plate. The moving calibration is used to make an AIM model in the motion capture system (MCS). The markers on the medial part of the ankle and knee can be removed afterwards during gait measurement to mitigate the risk of inadvertent touching between markers, depending on the participants way of walking.

Figure 13: Marker placement
Front view of marker placement on one of the participants

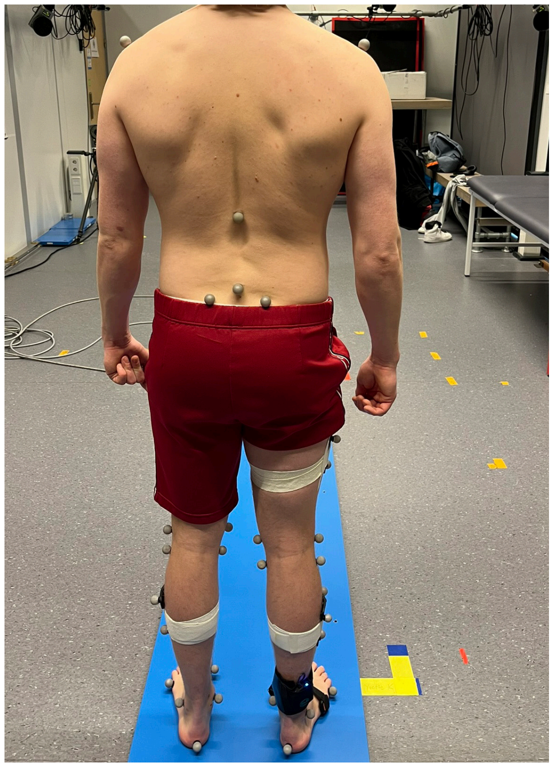

Figure 14: Marker placement
Back view of marker placement on one of the participants

4.1.4 KneeWear

The feedback system that is used are the sensors from Moveshelf and Elitac Wearables with the objective of instructing the participant to modify their FPA. Participants are briefed on the functionality of the feedback system before walking. Subsequently, participants are asked how they expect to react to the haptic feedback, whether they expect to move towards or away from the vibration with their foot. Indicating how the feedback system should be worn. This is important for the development of the KneeWear product. If both movements are approximately equally divided, this alteration should be implemented in the product.

4.2 Motion test

At the start of this experiment the participants have an opportunity to practice walking with the feedback system. All FPA modifications are practiced by the participant before measuring is started. As long as the participant needs before feeling comfortable and is able to take multiple steps within the asked FPA. Once participants are familiarized with the feedback system, the official measurements of the experiment begin.
The right limb is chosen for each participant to measure are wear the feedback system. One limb is used to limit the variations within the tests. For the FPA a range of 5° was chosen based on pilot trials. With a range smaller than 5°, it was unfeasible to execute more than one step within this specific interval. Resulting in toe-in and toe-out 5° being set at a range from 5° to 10°. And toe-in and toe-out 15° was set to a range from 18° to 23°.

4.3 Final tests

Participants are instructed to initiate the experiment by walking in their normal gait pattern for a duration of two minutes. The normal gait value serves as the baseline, for comparison with the different FPAs. Subsequently, participants undergo gait with the different toe-in and toe-out values, with the sequence randomized for all participants. For these gait modifications, participants are asked to stand still for five seconds at the beginning and end of the catwalk to recalibrate the Xsens DOT sensor, ensuring accurate alignment for the direction of walking. It is highlighted that participants start and recalibrate with their comfortable, normal angle. Thus the FPAs are measured from each participant's personal baseline.
Each toe-in and toe-out modification is assessed during a two minute walking interval, aligning most literature that did tests with FPA. (Shull, Shultz, et al., 2013) (Shull et al., 2011) (Karatsidis et al., 2018) (Shull, Silder, et al., 2013) (Uhlrich et al., 2018) (Seagers et al., 2022b) Between each altered walking pattern the participant can walk in their normal gait pattern for 30 seconds without getting any feedback to allow participants to normalize their gait. (Karatsidis et al., 2018) This experiment will show the effect of altering the FPA on the KAM for each individual for the four different angles. Additionally, participants are observed during by the executer whether they walk very different compared to normal gait.

4.4 Data processing

4.4.1 Questionnaire

To obtain answers about the comfort of the feedback system, a questionnaire is administered to participants to fill in after testing, Appendix A. Questions regarding users' perception of how well they understand the feedback system are posed.Additionally, the user is asked for possible improvements. Initially, the focus is on investigating the comfort level of the haptic feedback system. Subsequently, participants are asked about the comfort, discomfort and pain experienced in the knee and other lower limb joints due to alterations in FPA.

4.4.2 Calculating FPA

The FPA is measured during the midstance phase, when the foot is flat on the ground. (Jiménez et al., 2010) (Qiu et al., 2020) This moment is when the GRF is perpendicular to the bottom of foot. The FPA is measured in the horizontal plane by drawing a line between the midpoint of the 1st metatarsal head and the 5th metatarsal head, and the calcaneus. (Shull et al., 2011) The angle between this line and the walking direction is the FPA. The walking direction is defined as the line from the marker on the calcaneus's position at the midstance to the next midstance index. The angle is measured of the *i*th step by using the markers on the calcaneus and the metatarsal heads. A code is written in Matlab to obtain the FPAs, appendix E. This code is also used to count the amount of steps within the asked FPA according to the motion capture system. Being able to count how many correct steps participants are able to take. Saying something about the ease of use. The FPA is measured of the *i*th step when the foot is horizontally positioned on the ground. The foot vector $r_{f,i}$ is defined by (figure 15). (Karatsidis et al., 2018)

Formula 1

$$r_{f,i} = p_{t,i} - p_{h,i}$$

Formula 2

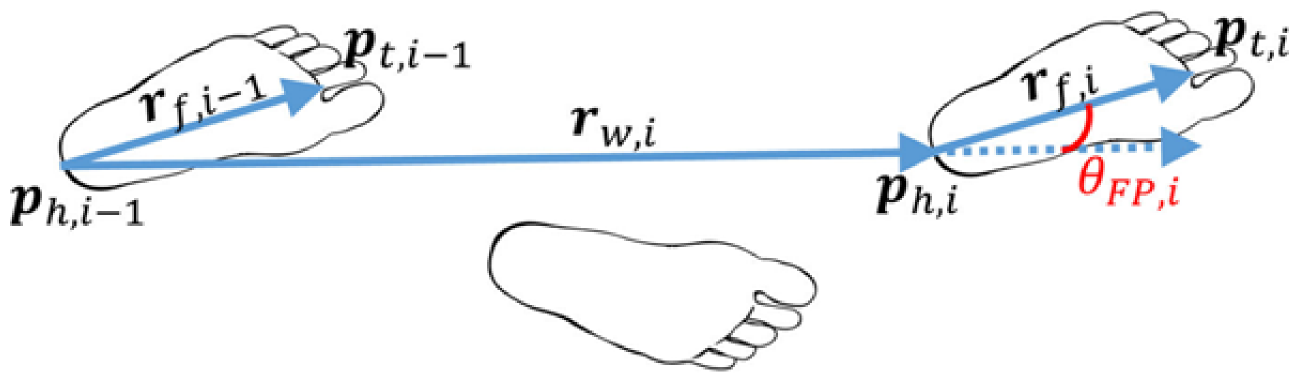

Figure 15: Calculation of FPA
Calculating the foot progression angle for the right foot (looking from below). The foot progression angle (ϑ_{FP}) of the ith step is derived from the difference of foot vector (r_f) and vector defining the direction (r_w). The vectors are computed based on the positions of the heel (p_h) and toe (p_t) as illustrated in the figure. (Karatsidis et al., 2018)

The FPA, $\theta_{FP,i}$, of the *i*th step is derived from $r_{f,i}$ and $p_{h,i}$

$$cos(\vartheta_{FP,i}) = (p_{h,i})/(r_{f,i})$$

4.4.3 Calculating KAM and KFM

The KAM and KFM are estimated by using force plates for recording the GRF and CoP, coupled with an optoelectronic marker system for 3D recording of the knee position. Several studies (Schache et al., 2008, Schache et al., 2006, Manal et al., 2002) use force plates to measure the GRF and CoP. After the tests are done, the first step is to make the AIM model (Automatic Identification of Markers). To easily label all the markers during the entire measurement. For each gait one step is searched that fits the requirements, when no step is found that fits to the requirements, that measurement is excluded from this research:

- Every marker is visible by the cameras of the Qualisys system
- Only one foot is located per force plate
- The GRF is located correctly below the right foot

When one gait cycle is found that fits to the requirements, the part starting from heel strike to toe-off is used. Heel strike is the moment when the GRF is greater than 25 Newton, toe-off is the moment the foot is not in contact with the ground anymore, so when the GRF is zero Newton. Toe-off ends the stance phase. After stance phase the swing phase starts, this is the entire phase that the researched limb is not in contact with the ground. (Nandy et al., 2021) Then the file is exported from Qualisys to a matlab file. Second, the matlab file is converted to a .mot and .trc file with a matlab code, appendix E. These files are necessary to extract the data in OpenSim. OpenSim is used to scale the models, for each participant a static scaled model is made. Here the static measurements are implemented. The subtalar angle and mtp angle are locked within the models. Lastly, the KAM is added wihtin OpenSim to calculate, since this is not automatically included. Within OpenSim inverse kinetics and dynamics analysis are applied. Finally the values of the KAM and KFM are extracted from the .xml file and inserted in matlab to create the graphs. From the graphs the biggest peak values for both moments are used for the measurements. (Foroughi et al., 2009) (Chehab et al., 2014) The moments are normalized to the weight and height of each participant, since the GRF, CoP and the knee position are factors that can be influenced by the body mass. (Lindsey et al., 2021) (Foroughi et al., 2009)

4.4.4 Calculating gait parameters

When adapting the FPA to reduce the KAM, other gait parameters are also influenced; gait speed, stride length, step width, trunk lean, and medial thrust. The gait speed is measured with Qualisys by measuring the distance of a gait cycle and the time needed for this. Stride length is the distance between the calcaneus when the right foot is flat on the ground to the moment the right foot is flat on the ground again. When the GRF is perpendicular below the foot this moment is chosen as 'foot flat on the ground'. Step width is the distance between the marker on the right calcaneus and the marker on the left calcaneus. To measure the trunk lean, a line can be made between the right posterior superior iliac spine and T1 in the frontal plane. This line can be compared to the static posture of the participant to compute the trunk lean to the right. Medial thrust is measured by the distance between the marker on the medial epicondyle on the right knee and the midline of the body. All values for the gait parameters are measured during the stance phase that is also used to measure the KAM and KFM.

4.4.5 Calculating lower limb kinetics

For the measurements on the lower limb kinetics there is focused on the ankle and hip joint. Calculations of moments in different joints involve the creation of a coordinate system per joint, each requiring at least three markers on anatomical landmarks to measure the moments. (Davis et al., 1991) With the scaled OpenSim models where the .xml files are extracted from. Are also used to calculate the moments at the hip and ankle joint. These calculations incorporate the GRF and moments from the force plate.The graphs are made by extracting the columns from the .xml file into Matlab.

To compare hip and ankle moments during normal gait with those during gait modifications, two different parameterization methods were employed due to limited literature on measurement methods:

1. The moment at the peak
2. The area under the curve of the hip and ankle moment during stance phase

The first parameterization method, focusing on peak moments, looking at the maximum moment of the hip and ankle joint during the stance phase. However, calculation with the peak moment ignores the overall load experienced by the joint. The second method, uses the area under the curve, considing the total hip and ankle moment over the entire stance phase. Capturing both magnitude and duration of the moments. This reflects the cumulative load on the hip and ankle joint, offering insides into joint health and disease progression.
For hip rotation moments the calculations are performed for the first peak only, since this is the greater peak. For hip adduction moment the value of the bigger peak is taken. Hip flexion moment and ankle angle moment show only one distinctive peak that is taken for the results.

5. Statistical analysis

Within this thesis a statistical analysis is done using SPSS. First a repeated ANOVA test is done, since all participants are subjected to different gait modifications, and the responses are analyzed. The goal is to find out whether there is a difference between the peaks that are formed when applying the different FPAs. When the findings appear to be statistically significant ($p < 0.05$), the next step is to do a pairwise comparison, a Bonferonni post hoc test is applied. This indicates where the statistical differences occur. This repeated ANOVA test with possible post hoc test is applied for comparison of the peak KAM, and peak KFM with the gait modifications.

For the hip and ankle moments a repeated ANOVA test is also applied. To find the statistical differences between the moment and the gait modification, for both parameterization methods. However, here instead of a Bonferonni post hoc test, Sidak post hoc test is applied. This since the Bonferonni test resulted in $p = 1.000$ for all comparisons. This indicates something went wrong.

Besides the repeated ANOVA test and post hoc, also a correlation test is done for the different gait parameters. This test is included to examine the correlation between the KAM and the gait parameters. These tests show a linear line with a correlation coefficient (R2). This coefficient shows value of the correlation is. R2 is a value between 0.0 and 1.0, a value of 1.0 presents a perfect correlation. The lower the coefficient, means a worse correlation.

Part III
Results

03

6. Results

20 participants completed the tests. The participants included have a mean value ± SD age of 23.35 ±2.35 years, weight of 63.925 ± 11.04 kilograms and height of 171.3 ± 8.98 centimeters. Table 1 provides an overview of the participants' characteristics.

Characteristics n = 20	***Mean ± SD***
Age (year)	23.35 ± 2.35
Height (centimeters)	171.3 ± 8.98
Mass (kilograms)	63.93 ± 11.04
Gender	M: 4 F: 16
Participants who reduced peak KAM with modified FPA	Peak 1 only: n = 1 Peak 2 only: n = 0 Peak 1 and peak 2: n = 13 None: n = 1
Neutral gait speed (m/s)	1.14 ± 0.24
Neutral stride length (meters)	1.24 ± 0.11
Neutral trunk lean (degrees)	8.46 ± 1.24
Neutral step width (centimeters)	0.75 ± 0.31

Table 1: Characteristics
Characteristics and mean ± SD values of the participants

The FPAs participants walked on average during the analyzed measurements are; Normal gait: -3.08° ± 6.04°, toe-in 5°: -4.94° ± 3.78°, toe-in 15°: -15.02° ± 4.67°, toe-out 5°: 9.80° ± 2.73°, and toe-out 15°: 22.05° ± 3.50°.
To say something about how quickly participants were able to adapt the different angles, the average amount of steps within the asked range participants were able to take is noted; Toe-in 5°: 10.5 good steps, toe-in 15°: 6.54 good steps, toe-out 5°: 7.57 good steps, and toe-out 15°: 8.69 good steps. On average a participant is able to take 30 to 40 steps per measurement.
Within the twenty participants, five are entirely excluded, and five participants miss one of the FPAs. Resulting in a cohort of 15 participants used to answer the research questions. Appendix B provides the exclusion reasons for each measurement.

6.1 Question 1: Effect on lower limb kinetics and gait parameters

The first research question investigates the impact of FPAs on gait paramaters and on lower limb kinetics, specifically the hip joint and ankle joint. All values per person per FPA for the gait parameters are in Appendix B. Graphs with the hip and ankle moments are presented in Appendix C.

6.1.1 What is the effect of changing the FPA on spatiotemporal and kinematic gait parameters?

Table 2 (page 27) shows the effects on all five gait parameters when changing the FPA. First, participants in this study showed an average walking speed of 1.12 ± 0.24 m/s during normal walking. This speed decreases to 0.98 ± 0.23 m/s for toe-in 5°, 0.99 ± 0.24 m/s for toe-in 15°, 0.97 ± 0.22 m/s for toe-out 5°, and 0.93 ± 0.19 m/s for toe-out 15°. Participant P7 shows a high increase in gait speed for all gait modifications. P10 and P13 also increase all their gait speeds, conversely the other twelve decrease their gait speed.

Second, the average stride length for the participants in this study is 1.24 ± 0.12 meters for normal gait. For toe-in 5°, the average stride length is 1.11 ± 0.13 meters; for toe-in 15°, it is 1.05 ± 0.14 meters; for toe-out 5° it is 1.06 ± 0.19 meters, and for toe-out 15° it is 1.04 ± 0.13 meters. Most participants decrease their stride length when applying different FPA's, participant P8, P9, P14 and P18 show the highest decreases. Four out of fifteen participants increase their stride length.

Third, throughout this study, participants exhibited an average step width of 7.55 ± 3.11 centimeters during normal gait. This increases to 15.47 ± 4.46 cm for toe-in 5°, 16.95 ± 6.57 cm for toe-in 15°, 9.23 ± 3.27 cm for toe-out 5°, and

8.65 ± 3.05 cm for toe-out 15°. Thirteen participants increase their step width, only two participants do not increase the step width.

Fourth, the average trunk lean of the participants within this study are for static posture 4.54° ± 1.24°, for normal gait 8.45° ± 2.11°, for toe-in 5° 8.02° ± 2.88°, for toe-in 15° 8.49° ± 3.24, for toe-out 5° 8.59° ± 3.31°, and for toe-out 15° 7.98° ± 2.51°. Five participants have an increase in trunk lean of more than 5°, for most gait modifications.

Last, medial thrust that participants show within this study are 2.27 ± 15.98 millimeters during normal gait, -0.52 ± 10.97 mm for toe-in 5°, 7.36 ± 9.90 mm for toe-in 15°, -0.82 ± 14.78 mm for toe-out 5°, and 5.15 ± 14.54 mm for toe-out 15°. Half of the participants show an inward medial thrust for the gait modifications.
An overview of the gait parameters and whether participants increase or decrease this value overall is depicted in figure 16. Additionally, the average increase and decrease value for the gait parameters are mentioned.

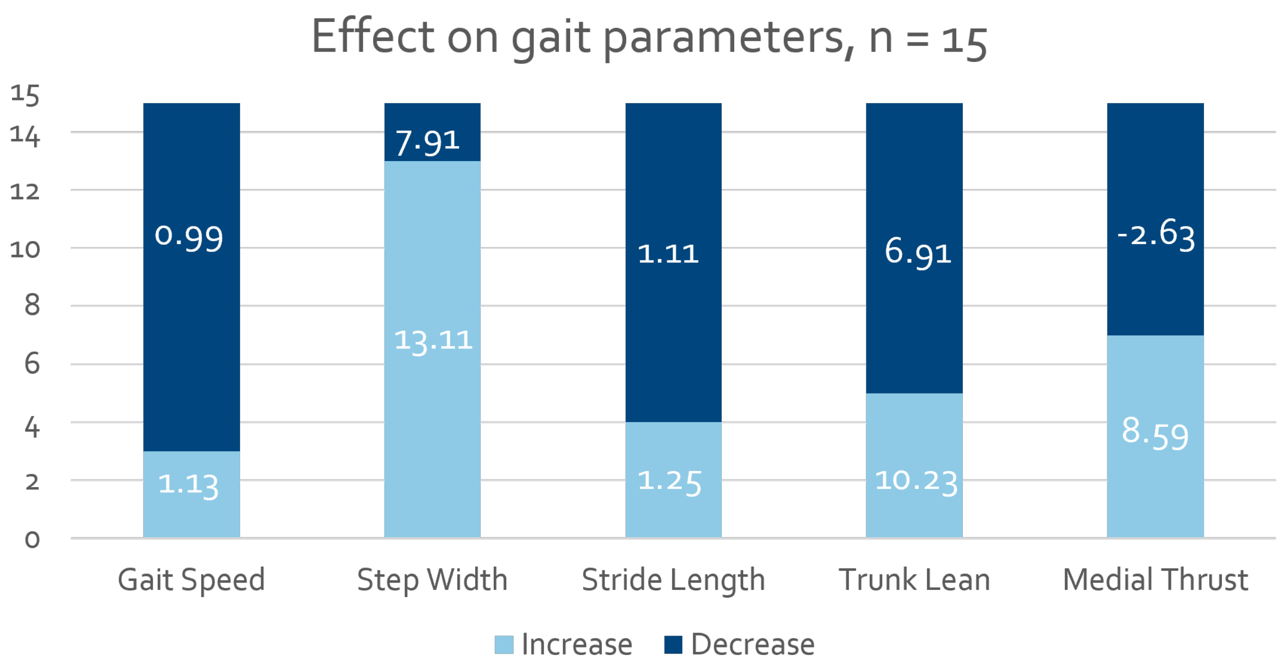

Figure 16: Distribution gait parameters
The distribution of the gait parameters over all FPA's, the dark blue shows the participants that decrease the parameters, and the light blue indicates the increases of the parameter. The numbers written within the graph depict the average increase or decrease per parameter. The gait parameters that are included; gait speed (m/s), step width (cm), stride length (m), trunk lean (degrees), medial thrust (degrees)

	Stride Length (m)				Trunk Lean (°)				Gait Speed (m/s)				Step Width (cm)				Medial thrust (mm)			
	TI 5	TI 15	TO 5	TO 15	TI 5	TI 15	TO 5	TO 15	TI 5	TI 15	TO 5	TO 15	TI 5	TI 15	TO 5	TO 15	TI 5	TI 15	TO 5	TO 15
P1	-0.11	-0.12	-0.06	-0.03	+3.76°	+2.31°	+3.12°	+2.3°	-0.01	+0.03	+0.04	0	-	-	-	-	6.4	-6.68	-8.94	26.85
P2	+0.08	+0.03	+0.04	+0.05	+5.48°	+5.1°	+5.88°	+3.78°	-0.01	-0.03	-0.02	-0.01	-	-	-	-	-0.51	-7.13	-24.63	18.42
P7	-0.03	0	+0.15	-0.06	+5.09°	+6.46°	+4. 9°	+2.76°	+0.11	+0.21	+0.07	+0.04	+1. 13	+1.97	-0.37	-0.37	-8.1	16.80	7.53	0.64
P8	-0.47	-	-0.29	-0.41	-0.52°	-	-0.01°	-0.05°	-0.87	-	-0.55	-0.56	+1.44	-	+0.23	+0.44	-14.47	-	-15.85	1.45
P9	-0.29	-	-0.27	-0.35	+4.53°	-	+8.05°	+5.14°	-0.17	-	-0.16	-0.17	+0.59	-	+0.37	-0.03	28.29	-	18.91	20.37
P10	+0.01	+0.07	-0.17	-0.15	+0.84°	+4.17°	+1.74°	+1.86°	0	+0.22	+0.12	+0.09	+0.33	+0.54	+0.2	+0.24	-5.6	15.57	-10	-7.14
P11	-0.15	-0.13	-0.18	-	+6.81°	+8.55°	+8.64°	-	-0.1	-0.09	-0.1	-	-0.33	-0.41	-0. 55	-	-9.93	17.96	-5.73	-
P12	-0.15	-0.23	-0.08	-0.17	+4.17°	+2.32°	+4.79°	+2.65°	-0.35	-0.49	-0.04	-0.39	+0.9	+1.75	+0.5	+0.58	2.00	-1.33	0.87	16.77
P13	0	-0.14	-0.04	-0.02	+2.85°	+2.32°	+3.86°	+3.9°	+0.08	+0.05	+0.12	+0.16	+0.24	+1.15	+0.15	-0.29	4.16	11.24	-2.95	-7.2
P14	-0.24	-0.23	-0.24	-0.32	+1.85°	+0.05°	+0.26°	+6.56°	-0.45	-0.44	-0.43	-0.49	+0.12	+0.19	+0.11	+0.03	-5.9	13.90	3. 95	-6.48
P15	-0.06	+0.03	-0.04	-	+5.25°	+3.95°	+5.05°	-	-0.12	-0.06	-0.32	-	+0.09	+0.57	-0.17	-	14.17	7. 19	20.7	-
P16	-	-0.05	+0.11	+0.08	-	+3.42°	+3.65°	+7.3°	-	-0.24	+0.06	-0.11	-	+0.95	+0.47	+0.51	-	20.01	-9.96	-15.56
P18	-0.16	-0.13	-0.67	-0.06	+1.76°	+2.13°	+1.93°	+1.83°	-0.26	-0.27	-0.29	-0.04	+0.76	+0.82	+0.29	+0.2	-4.26	1.87	-11.0	-3.03
P19	-0.16	-0.09	-	-0.09	+1.76°	+2.13°	-	+3.47°	-0.06	-0.01	-	-0.05	+1.07	+1.15	-	+0.05	-9.27	-5.08	-	-2.79
P20	-0.19	-0.3	-0.15	-0.25	+5.99°	+7.62°	+5.9°	+7°	-0.21	-0.20	-0.19	-0.14	+1.3	+1.73	+0.53	+0.62	-9.26	11.36	25.58	24.68

Table 2: Gait parameter changes

The effect of changing the FPA on the different gait parameters, all parameters are compared to normal gait; the stride length is expressed in meters, trunk lean is described in degree, gait speed is depicted in m/s, step width is in centimeters, and medial thrust shows the difference in millimeters.

6.1.2 What is the effect of changing the FPA on lower limb kinetics?

The moments within the hip and ankle joint are measured during the different FPAs. It is researched whether the moments in the joints increase when participants change their gait.

First the hip flexion moment is measured and depicted in figure 17. The figure shows the two parameterization methods that are included, the peak value (dark blue), and the area under the curve (light blue). The line in the middle indicates the mean value for each FPA. It is shown that all mean values are below zero, and thus show an overall reduction in hip flexion moment. Additionally, the figure shows that the peak value has a wider distribution of all values compared to the values for the area under the curve.

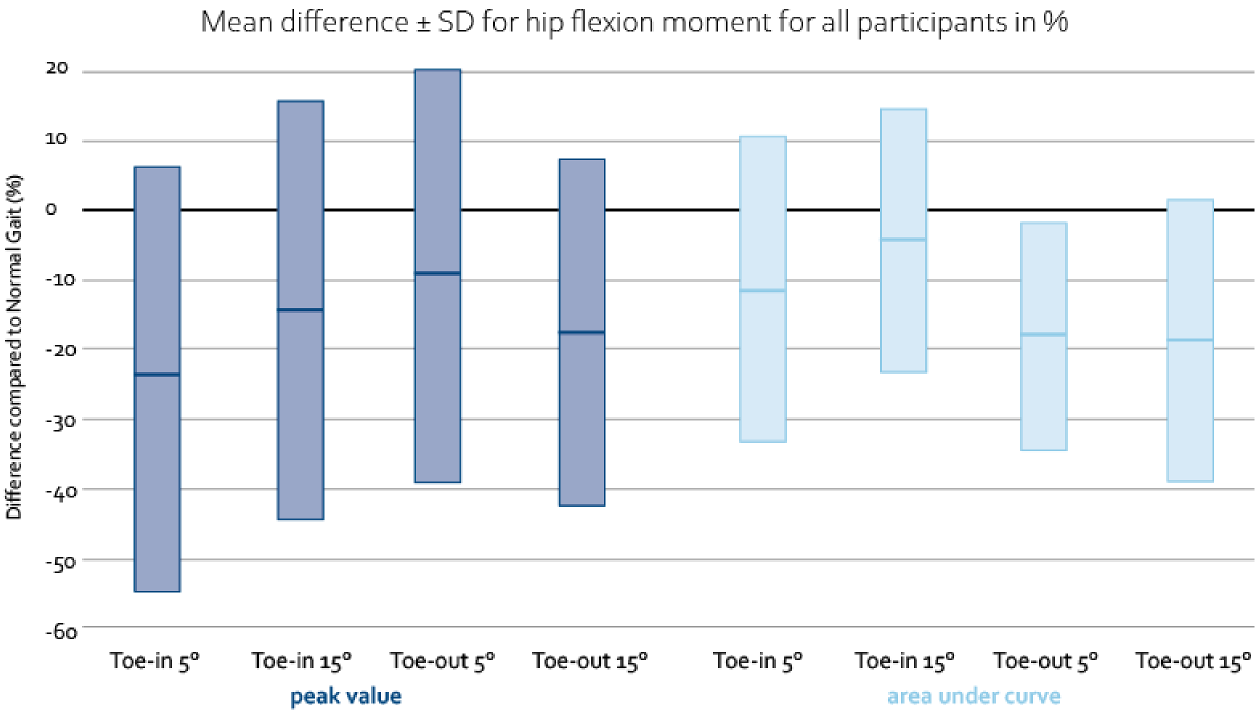

Figure 17: Graph mean ± SD for hip flexion moment
Graph that depicts the mean ± SD value for the hip flexion moment, the dark blue defines the moment at the peak value and the light blue defines the area under the curve for the moment. The dark line in the middle of each box defines the mean value for the measurement

When calculating the hip adduction moment, figure 18 results from this. Again the dark blue lines depict the peak value, and the light blue depicts the area under the curve. The peak value shows only mean values above zero, while the area under the curve has only a mean value above zero for toeing-in 5°. Indicating different interpretations per parameterization method, the peak value of the hip adduction moment increases, while three out of four for the area under the curve decrease the hip adduction moment.

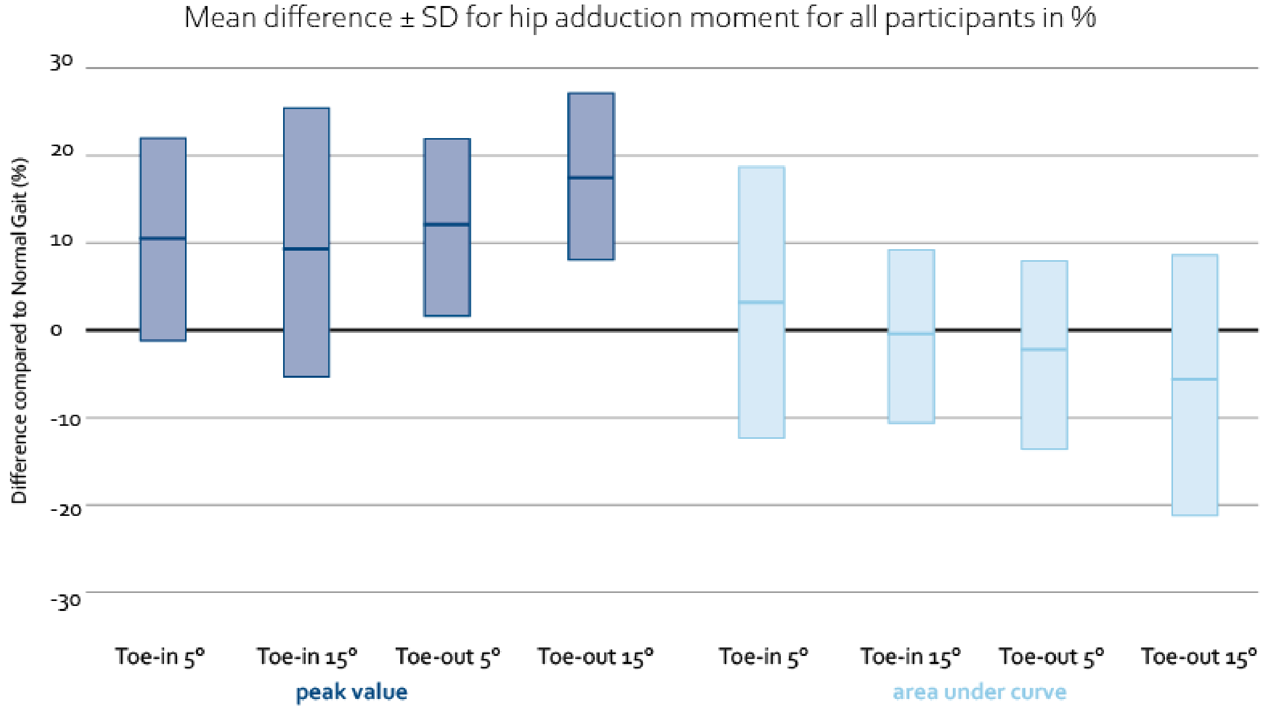

Figure 18: Graph mean ± SD for hip adduction moment
Graph that depicts the mean ± SD value for the hip adduction moment, the dark blue defines the moment at the peak value and the light blue defines the area under the curve for the moment. The dark line in the middle of each box defines the mean value for the measurement

The hip rotation momen, shown in figure 19,t increases slightly for three out of four FPAs when measuring the peak value. These mean values are all below a 10% increase compared to normal gait. Conversely, the mean values for the area under curve result in three out of four showing a reduction in mean value. The peak values are wider distributed compared to the area under the curve.

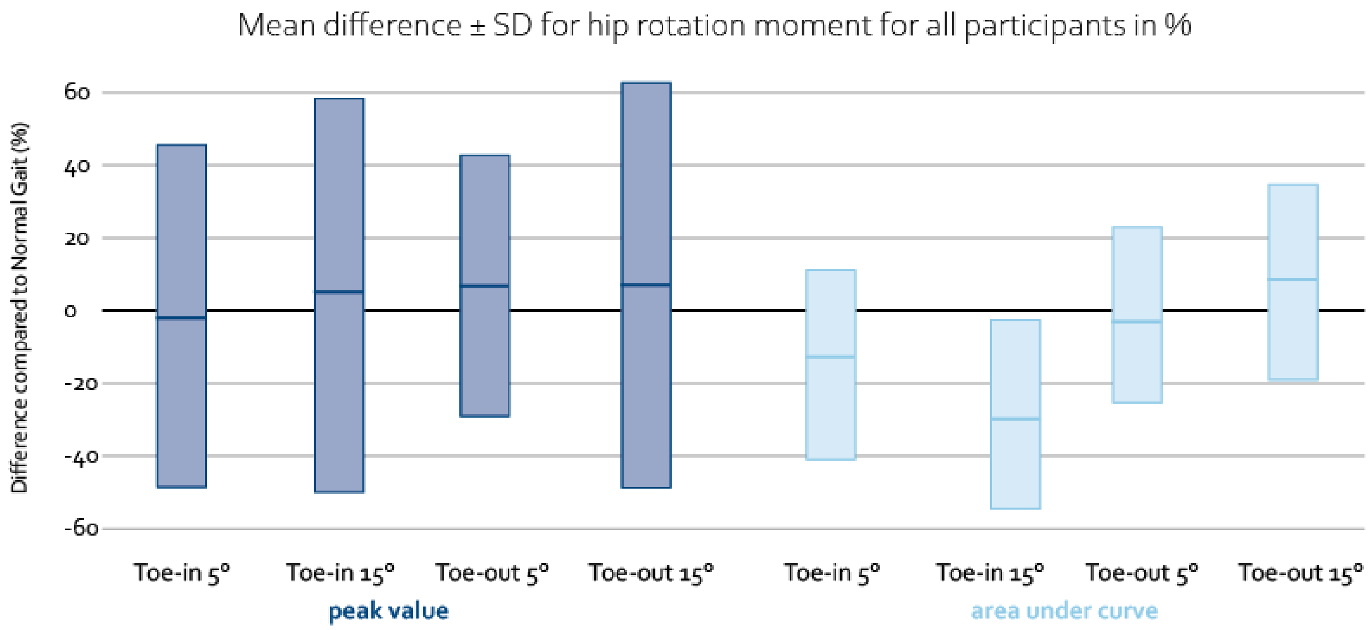

Figure 19: Graph mean ± SD for hip rotation moment
Graph that depicts the mean ± SD value for the hip rotation moment, the dark blue defines the moment at the peak value and the light blue defines the area under the curve for the moment. The dark line in the middle of each box defines the mean value for the measurement

Figure 20 depicts the mean values for the ankle moment. Both parameterization methods show an increase in mean value for the same three FPAs, only toe-out 15° decreases the mean value. Notably is that toe-out 5° has a wide distribution of values compared to the other values.

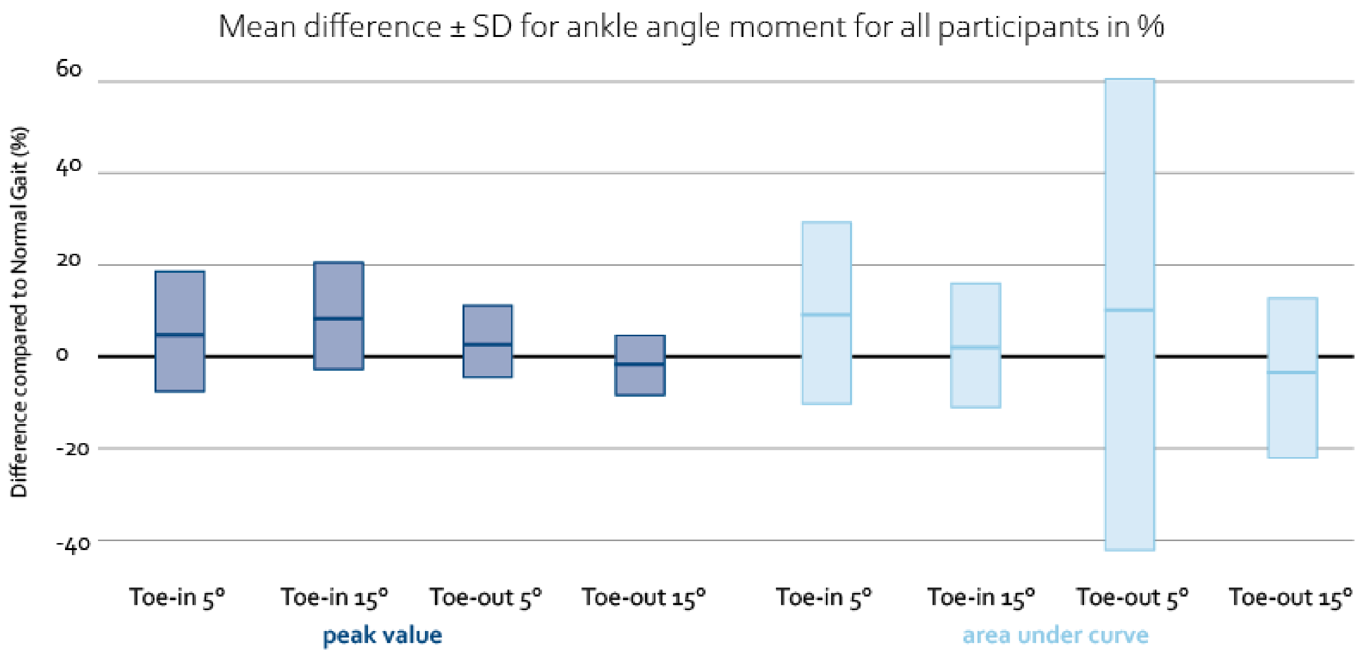

Figure 20: Graph mean ± SD for ankle angle moment
Graph that depicts the mean ± SD value for the ankle angle moment, the dark blue defines the moment at the peak value and the light blue defines the area under the curve for the moment. The dark line in the middle of each box defines the mean value for the measurement

6.2 Question 2: Effect of modifying the FPA on the KAM and KFM

The impact of FPA adaptations on the 1st and 2nd peak KAM (pKAM) among participants are calculated. In appendix C all graphs with the pKAM and peak KFM (pKFM) moments are depicted. Additionally, tables are provided in the appendix with the percentage increase or decrease per participant per FPA compared to normal gait. A reduction in pKAM of 5% or more is, according to literature (Shimada et al., 2006), associated with improved knee moment and pain. For the normal gait, the mean peak value ± SD for the 1st pKAM is 2.77 ± 0.77 Nm/kg, for the 2nd peak this mean value is 2.34 ± 0.62 Nm/kg. Next, the mean values ± SD are calculated for the FPAs. These values for the pKAM and pKFM can be seen in figure 21 and 22.

Figure 21 depicts the mean values for the pKAM. The dark blue boxes are the values for the 1st peak, and light blue shows the mean values for the 2nd peak. It can be seen that the mean values for the 1st peak all decrease, while for the 2nd peak only the toe-out mean values decrease. Additionally, the 2nd peak shows the highest mean decrease during toeing-out 15°.

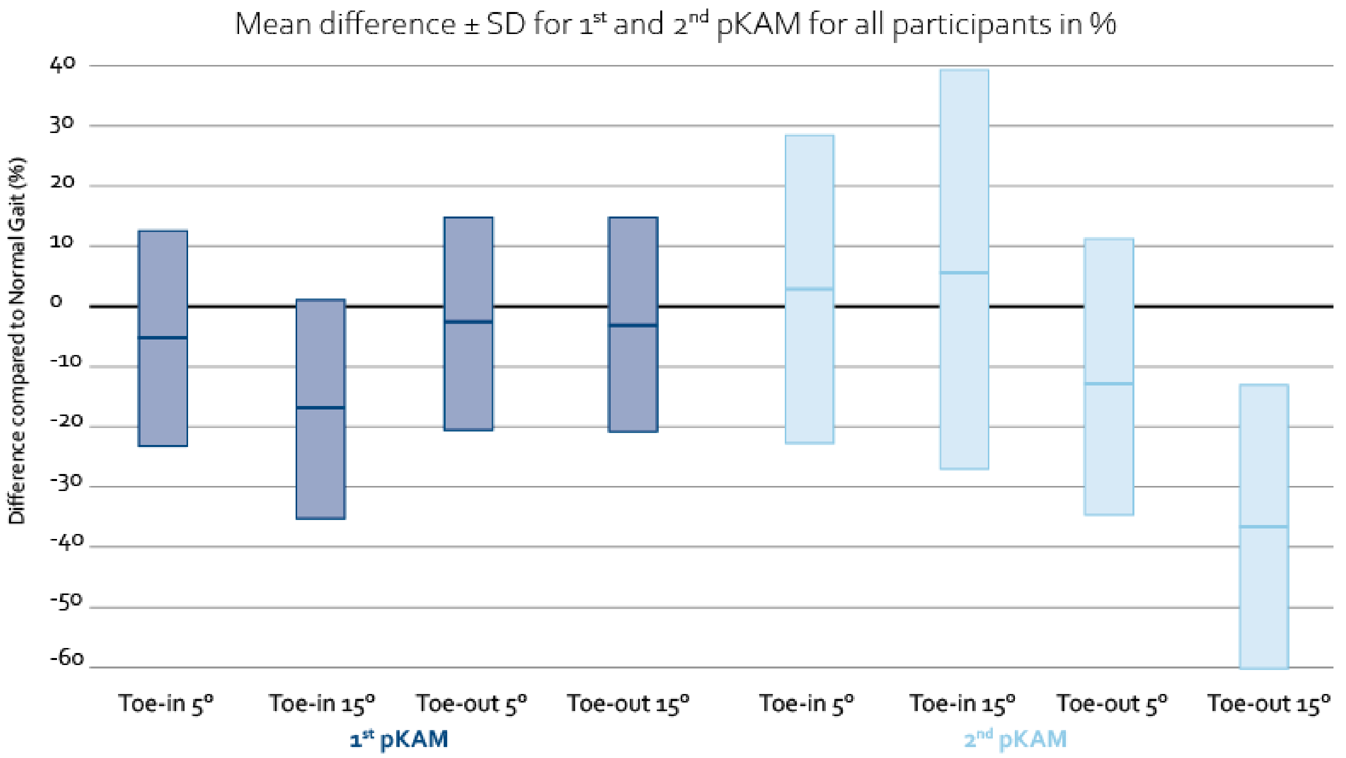

Figure 21: Graph mean ± SD for pKAM
Graph that depicts the mean difference ± SD value for the two pKAM's, the dark blue defines the 1st pKAM and the light blue defines the 2nd pKAM. The dark line in the middle of each box defines the mean value for the FPA

Current studies, (Foroughi et al., 2009) (Chehab et al., 2014), primarily emphasize the focus on reducing the largest pKAM. Fourteen out of fifteen participants show a larger 1st pKAM, one participant showed a larger 2nd pKAM. Measuring the overall decrease in the largest pKAM for each person reveales a reduction of 8.58 ± 27.57%.

On individual level nine participants show a decrease in 1st pKAM with the smaller toe-in angle, twelve show a decrease in 1st pKAM with the larger toe-in angle. Ten decrease their 2nd pKAM with the smaller toe-out angle, whereas thirteen decrease their 2nd pKAM with the larger toe-out angle.
Notable, P11 showed an increase in KAM for every gait modification.

Figure 22 contains the mean values for the two peaks in KFM. For the 1st pKFM the mean value increases during toeing-in, while the pKFM decreases during toeing-out. For the 2nd pKFM the values increase for all except toeing-out 15°. Additionally, it is notable that the deviation is higher during the 1st peak compared to the 2nd peak, especially withing toe-out 15° during the 1st peak there is a high deviation.

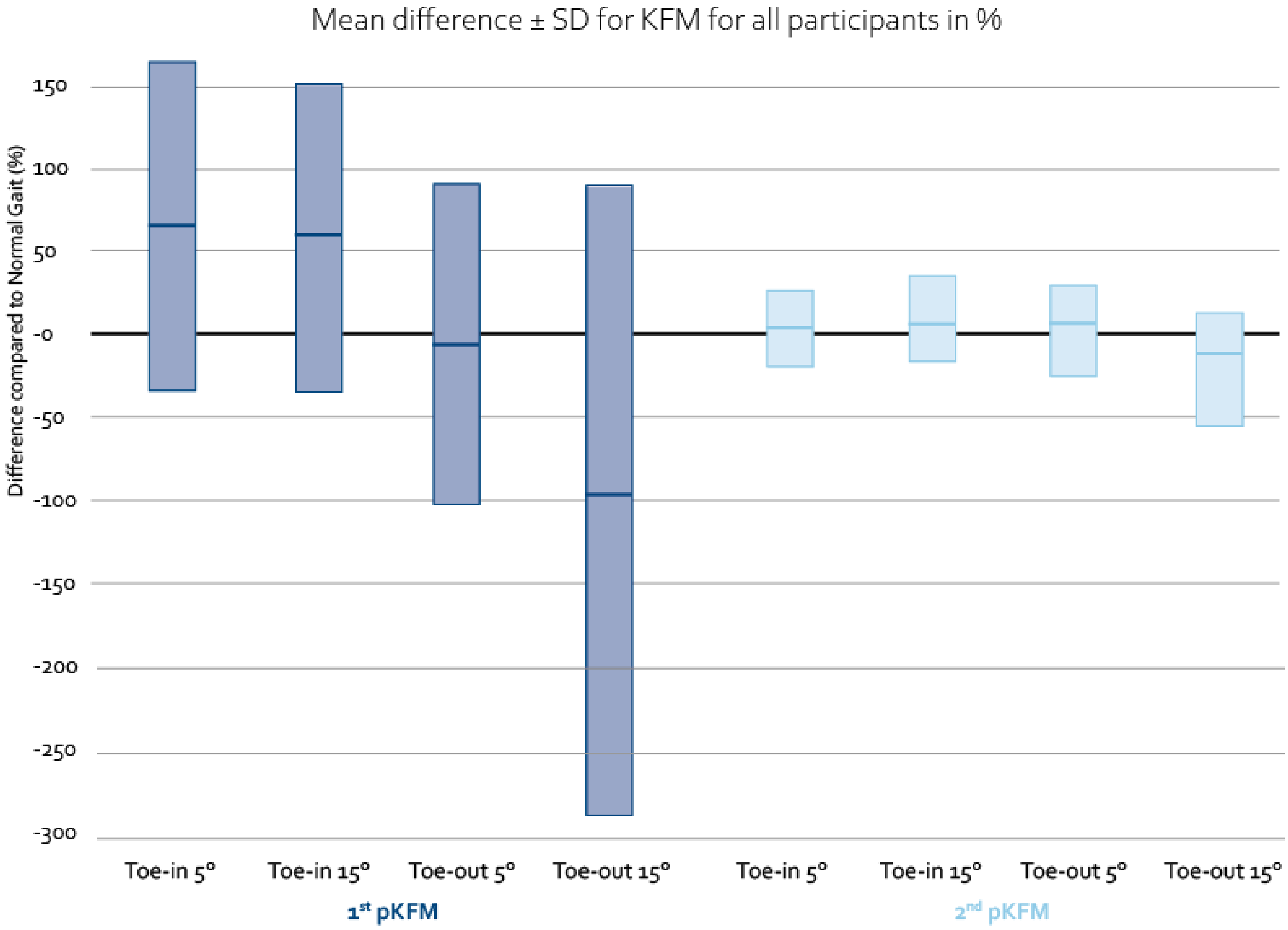

Figure 22: Graph mean ± SD for KFM
Graph that depicts the mean ± SD value for the KFM, the dark blue efines the 1st pKFM and the light blue defines the 2nd pKFM. The dark line in the middle of each box defines the mean value for the measurement

The main differences between figures 21 and 22 are that the y-axes with figure 22 contains higher values. Within the pKFM the axes is between -300% and 150%, while for the pKAM this is between -60% and 40%. Both figures show a mean decrease for toeing-out 5° and 15° when looking at the 1st peak, and both show a mean decrease for toeing-out 15° during the 2nd peak. During the 1st peak both toeing-in angles show contrary results for pKAM and pKFM.

Both the KAM and KFM give information about the load in the knee, besides looking at the results of the group, it is alos important to include personalized results. Figure 23, next page, shows the change in pKAM and pKFM for each FPA per participant. This figure shows the change within the peaks in Nm/%BW*Ht. The circles indicate the toe-in values and the squares indicate the toe-out values.
The importance of this image is to find out whether the load in the knee decreases. When a decrease in pKAM is found, it does not necessarily result in also a decrease in pKFM. Both values are wished to decrease to release the knee joint from forces.

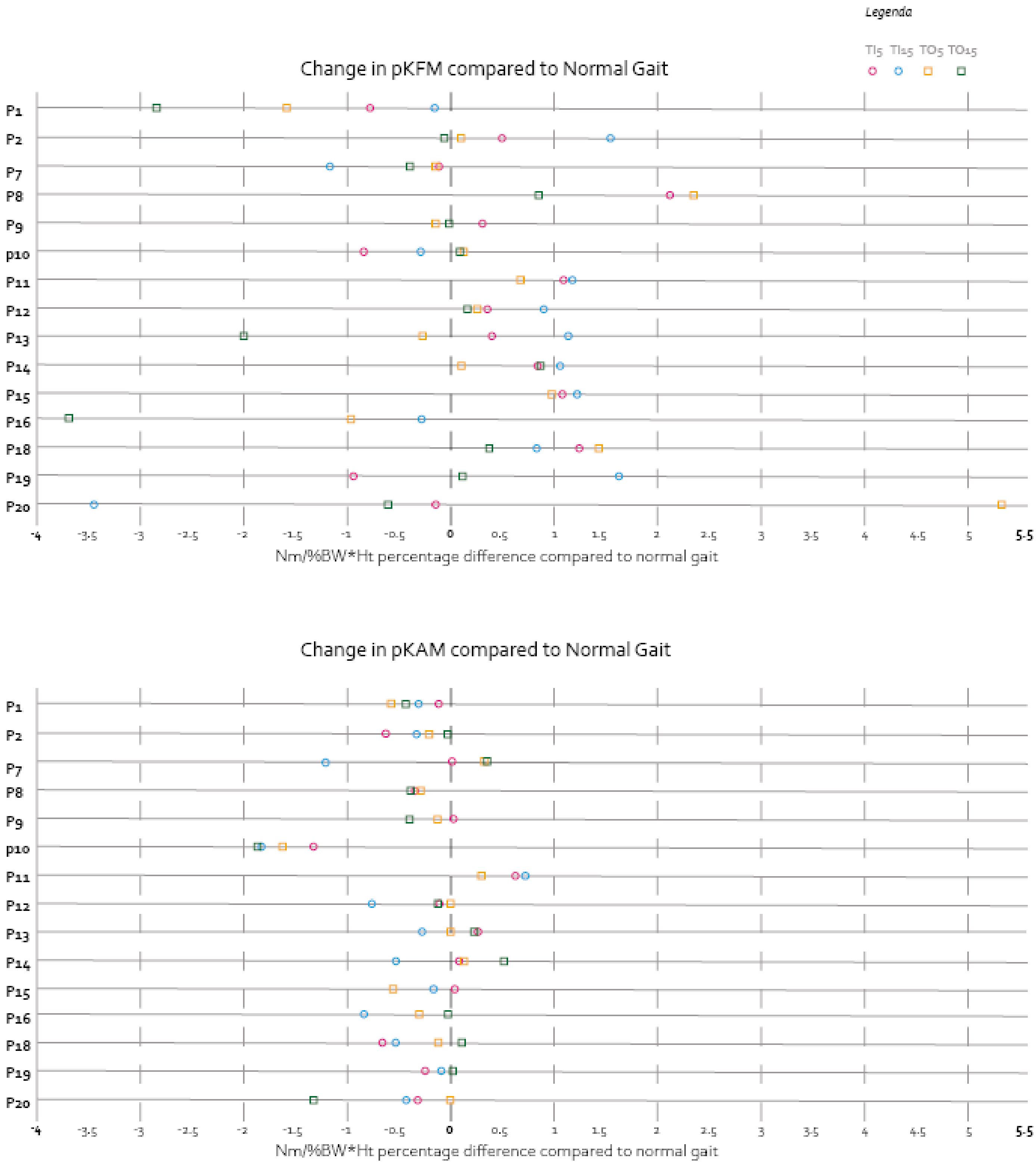

Figure 23: pKAM and pKFM compared to normal gait

*The two figures depicted above indicate the change in pKAM and pKFM compared to normal gait for each FPA. On the y-axes the participants are depicted, on the x-axes the difference in Nm/%BW*Ht compared to normal gait is depicted for the FPAs. The circles depict toeing-in, and the squares depict toeing-out. The upper graph shows the pKFM and the lower graph shows the pKAM. For the moments the peak that is chosen is the what was the biggest peak for each participant.*

6.3 Question 3: Usability and comfort of the haptic feedback system

Prior to the tests participants were asked whether they expect to turn their foot away from the feedback or towards the feedback. Figure 24 illustrates eleven participants moving away from the feedback, while nine participants moved towards it.

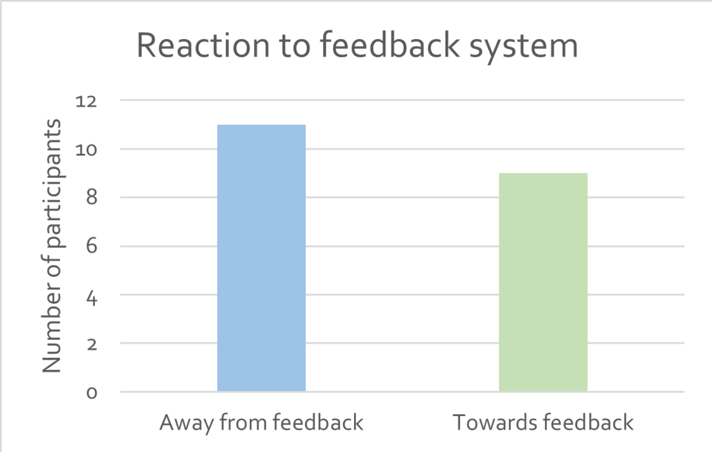

Figure 24: The reaction to the feedback system
The preference of the participants how to react to the feedback, towards the feedback (9 participants) or away from the feedback (11 participants)

At the end of the tests, participants were asked whether they preferred walking with a toe-in or toe-out gait. As depicted in figure 25, eight participants preferred toe-in gait, while twelve participants preferred toe-out gait.

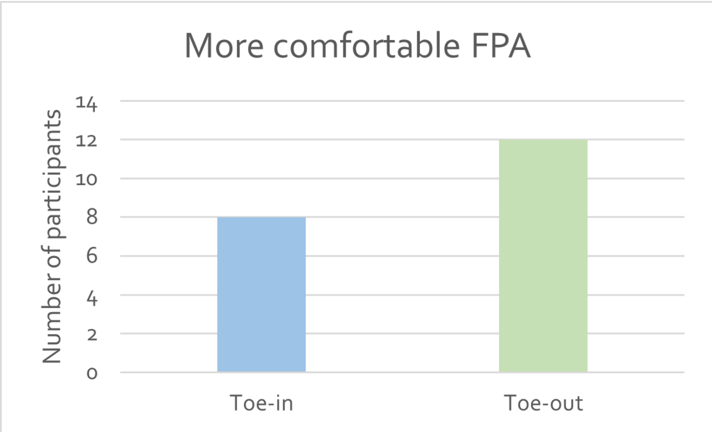

Figure 25: Preferred FPA
The preference of the participants for more comfortable walking, toe-in (8 participants) or toe-out (12 participants)

When the tests were concluded, the participants were asked to fill in a questionnaire. The questionnaire consists of four questions, each being discussed below.

6.3.1 Did you find the feedback system around the ankle comfortable or uncomfortable?

None of the participants reported the feedback system uncomfortable. Participants' comfort level ranged from feeling 'very comfortable' to 'just comfortable'.

6.3.2 How quickly did you understand the feedback system? Did it feel like you mastered walking at the required angle with your feet quickly?

Participants found it challenging to walk at the required angles. The difficulty varied based on each participant's preferred angle, with some requiring significant time to achieve the desired angle. Each gait modification was recorded for two minutes. During the measurements, participants were able to achieve a maximum of four consecutive steps within the target range. The range was ± 2.5 degrees, which was necessary to allow participants the possibility to take multiple steps without receiving feedback. A smaller range would have made this impossible.

6.3.3 Was the gait adaptation with the different angles comfortable, or did it cause pain in other joints?

None of the participants reported pain in other joints. However, most experienced discomfort. Participants noted increased stiffness in their knees and ankles, the ankle joint felt as it was not moving through its full range of motion. Another comment and observation was that participants walked with their head down, focusing on the location of their toes. This focus resulted in slower walking speeds and smaller steps, and change in their posture.

6.3.4 Do you have any additional comments about the feedback system and walking at the required angles?

The questionnaire provided valuable insights on the feedback system. Participants reported feeling the haptic feedback at a regular interval. Resulting in feeling feedback when the foot is on the ground, but also when the foot is in the air. This caused confusion, and participants expressed a preference for no vibration when the foot is off the ground.

Second, several participants inquired about the intensity of the vibrations. They suggested that varying the intensity of the vibrations could help them achieve the desired angle quicker. For instance, a more intense vibration indicates a larger deviation from the target angle, while a milder vibration indicates a smaller deviation from the angle.

Third, after prolonged exposure to haptic feedback, participants struggled to notice whether the vibrations were on the medial or lateral side of the malleoli. Complicating the ability to react accordingly to the vibration.

Observations revealed that participants tended to change their posture during alterations in FPA. They stiffen the left side of their bodies, as they focused only on adapting the angle of the right foot, where the feedback was given. This focus resulted in the left foot remaining in its normal angle. When instructed to participants to focus on altering the angle of both feet, participants could do so for only a few steps before reverting to their previous pattern.

Other observations were that participants walked face down, focusing on the toes to alter for the correct FPA. Additionally, participants started walking with a squating down gait during the larger angles, they lowered their right shoulder during different FPAs. Participants moved their arms more lateral, and stiffened them during walking. During toeing-in it was noticed that participants moved both their knees more medial. Lastly, participants raised their feet less during FPA alterations and smaller steps were taken, probably a result from stiffening all lower joints.

7. Statistics

7.1 KAM and KFM

The repeated ANOVA test for the KAM is applied for nine participants, since six participants missed one FPA resulting in SPSS excluding the entire participant. Executing the repeated ANOVA tests for the FPA and pKAM a significant difference is found, $p = 0.002 < 0.05$. Within the post hoc test this significant difference is found between normal gait and toe-in 15° ($p = 0.025$) (Appendix D). No significant differences were found between the other gait modifications. For the pKFM the repeated ANOVA test is also executed for nine participants. Resulting in $p = 0.736 > 0.05$, so non-significant.

7.2 Hip and ankle moments

The repeated ANOVA test is also done for the hip and ankle moments, table 3. It can be seen whether there is a significant difference within the parameterization methods, and if yes between which gait modifications. Table 3 shows $p < 0.05$ for the hip flexion moment when measuring the area under the curve, and for the hip rotation moment, however the ANOVA test did not indicate where this significant difference was within the hip rotation moment.
The detailed tables for post hoc tests are depicted in Appendix D.

Moment	*Parmeterization method*	*p-value ANOVA*	*Post hoc*	*p-value post hoc*
Hip flexion moment	Peak value Area under curve	0.498 **0.005**	None **NG vs. TO15**	 **0.013**
Hip rotation moment	Peak value Area under curve	0.953 **0.011**	None None	
Hip adduction moment	Peak value Area under curve	**0.036** 0.376	**NG vs. TO15** None	**0.001**
Ankle moment	Peak value Area under curve	0.288 0.155	None None	

Table 3: Statistical test hip and ankle moments
The statistical tests for the hip and ankle moments, the two parameterization methods are compared and research whether there are significant differences within the gait modifications. NG = normal gait, TI5 = toe-in 5, TI15 = toe-in 15, TO5 = Toe-out 5, TO15 = toe-out 15. The values are significant when p < 0.05.

7.3 Gait parameters

For the gait parameters, a repeated ANOVA test is done with post hoc test, table 4, and the correlation coefficient (R^2) is obtained, table 5. All exact tables and figures can be found in appendix D.

Gait parameter	*p-value ANOVA*	*Post hoc*	*p-value post hoc*
Gait speed	0.272	None	
Step width	**0.001**	**NG vs. TI15**	**0.039**
Stride length	0.310	None	
Trunk lean	**0.001**	**NG vs. TI5** **NG vs. TI15** **NG vs. TO5** **NG vs. TO15**	**0.004** **0.020** **0.006** **0.005**
Medial thrust	0.372	None	

Table 4: Statistical tests gait parameters
The statistical tests for the gait parameters, NG = normal gait, TI5 = toe-in 5, TI15 = toe-in 15, TO5 = Toe-out 5, TO15 = toe-out 15. The values are significant when p < 0.05.

Table 4 shows $p < 0.05$ for the step width and the trunk lean. Trunk lean shows a significant difference between all FPAs and the normal gait.

Gait parameters	*FPA*	*Correlation coefficient R^2*
Gait speed	Normal gait° Toe-in 5° Toe-in 15° Toe-out 5° Toe-out 15°	0.008 0.057 0.117 0.043 0.328
Stride length	Normal gait° Toe-in 5° Toe-in 15° Toe-out 5° Toe-out 15°	0.004 0.062 0.126 0.042 0.134
Step width	Normal gait° Toe-in 5° Toe-in 15° Toe-out 5° Toe-out 15°	0.012 0.260 0.407 0.185 0.030
Trunk lean	Normal gait° Toe-in 5° Toe-in 15° Toe-out 5° Toe-out 15°	0.488 0.110 1.431E-4 0.005 1.254E-4
Medial thrust	Normal gait° Toe-in 5° Toe-in 15° Toe-out 5° Toe-out 15°	0.012 0.405 0.605 0.009 0.377

Table 5: Correlation coefficients gait parameters
The correlation coefficients for the different FPAs and the gait parameters. When R^2 is close to 1.0, a more perfect correlation is found

Table 5 depicts whether there is a correlation between the different FPAs and the gait parameters that are measured. Focusing on the sub-question within this research whether changing the FPA effects the gait parameters. It shows that all correlation coefficients are between 1.431E-4 and 0.605, where most coefficients are below 0.50. This observation indicates that the correlation between the different gait parameters and FPAs are not close to 1.0, so no perfect correlation.

Also scatter plots are included of the pKAM and the different gait modifications. These figures are depicted on the next page, figure 26. These figures indicate that there is no clear linear relationship between the changing the FPA and the effect of this on the gait parameters. Every figure includes multiple outliers, confirming the values found in table 5 when measuring the correlation coefficients.

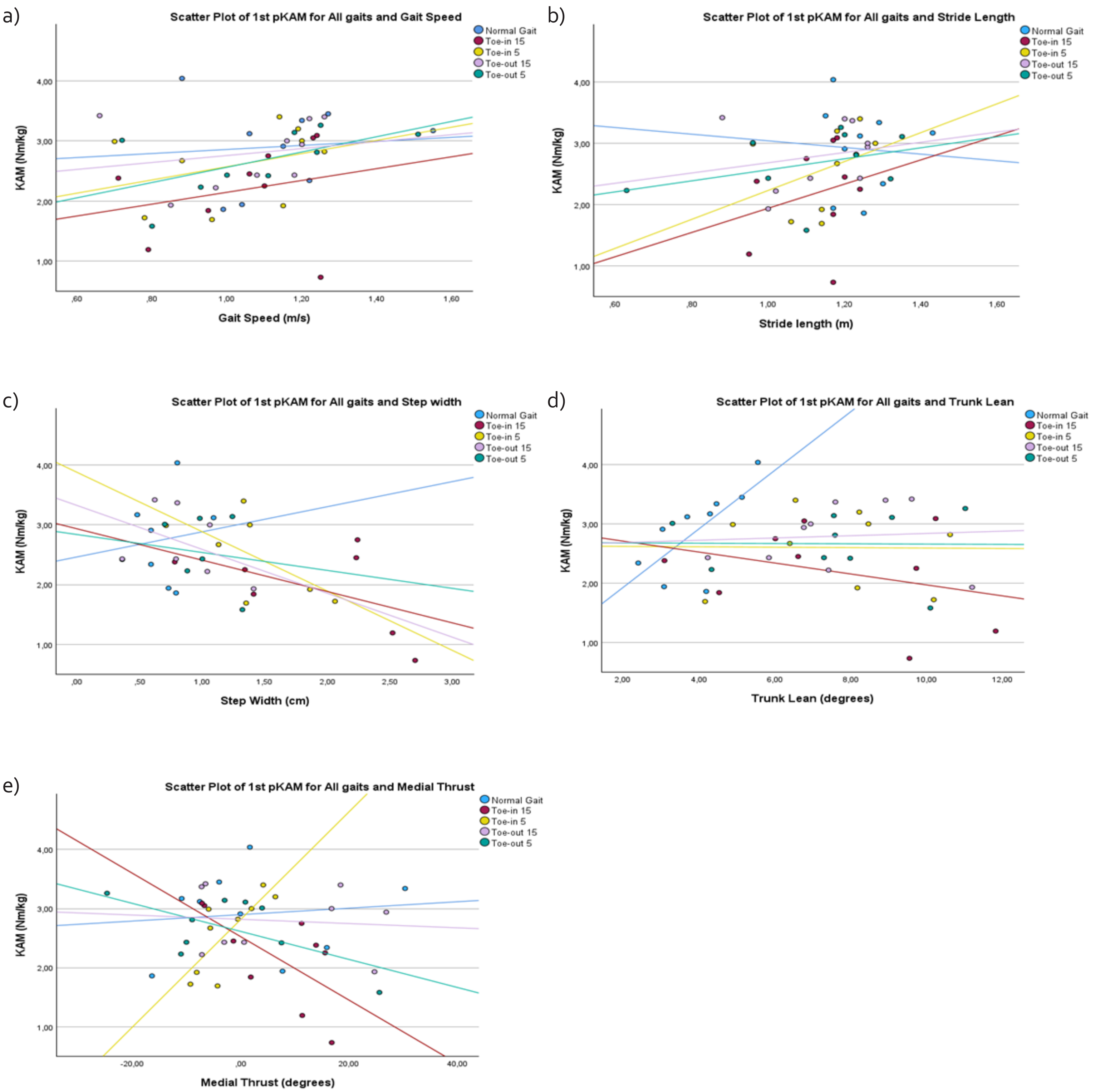

Figure 26: Quick overview of correlation gait parameters

A quick overview of the correlation of the different gait parameters, it shows that there are multiple outliers. a) gait speed, b) stride length, c) step width, d) trunk lean, e) medial thrust. The graphs are also depicted in appendix D when they are bigger for detailed view

Part IV

Discussion & Conclusion

04

8. Discussion

The objective of this study is to examine the influence of FPA modifications on lower limb kinetics and to investigate how changes in FPA affect gait parameters. It was hypothesized that altering the FPA would impact lower limb kinetics, though which moment would be most affected remained uncertain. Additionally, it is well established that variations in gait parameters can alter gait patterns. Therefore, it was anticipated that walking with different FPAs would influence posture and gait patterns, and thus gait parameters.
Moreover, this research incorporates the use of a haptic feedback system, designed to assist participants in adjusting their FPA. However, the number of steps participants were able to achieve within the desired FPA was lower than anticipated. On average, participants successfully performed one-fifth of the steps within the target FPA range. This difficulty highlights the challenge participants faced in achieving the correct FPA within the 5° range using the feedback system.

Effect of FPA on KAM

The measurement of the average reduction in the pKAM revealed an overall decrease of 24.42 ± 20.40%. According to studies, an average reduction of 18.6 ± 16.2% is found for the largest pKAM compared to normal gait, with the most substantial decrease documented at 77% in healthy participants. (Uhlrich et al., 2018) This thesis observed a maximum reduction for the biggest pKAM of 62.4%. However, the magnitude of pKAM reduction and the optimal FPA varied among participants, it differed whether participants decreased or increased their pKAM with each FPA, figure 27. Overall participants decreased their pKAM more. Some FPAs show fewer than 14 participants in figure 27, which is due to the exclusion of certain measurements.

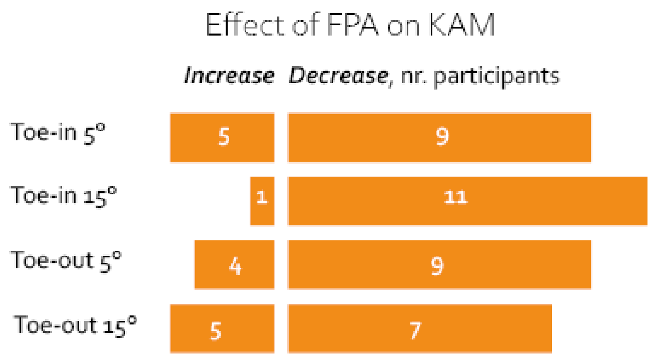

Figure 27: Distribution pKAM
This shows whether participants decrease or increase their 1st pKAM for the different FPAs

One participant had a larger 2nd pKAM, this participant achieved a maximum reduction by toeing-out 5°. The angle that yielded the maximum decrease in pKAM differed among participants, supporting the hypothesis that a personalized approached results in a greater reduction in KAM.
All participants, except one, demonstrated a decrease in their pKAM during at least one of the FPAs. Participant P11 exhibited an increase in all pKAM measurements. Despite the change in gait parameters, which typically would lead to a reduction in pKAM, this participant's increase in pKAM remains unexplained. A possibility is to include a larger toe-in or toe-out angle for the wished result. Additionally, further research is needed to investigate alternative adaptations and solutions.

Effect of FPA on KFM

Most existing literature primarily focuses on measuring the KAM, however, KFM also plays a significant role in influencing the load in the knee joint. (A. H. Chang et al., 2015) The KAM and KFM exert forces in different planes (Chehab et al., 2014), and a reduction in KAM does not necessarily lead to also a decrease in KFM. This distinction is important, as it suggests that certain FPAs that reduce KAM might simultaneously increase KFM, potentially leading to undesirable loading on the knee joint.
Participant P1 decreased the pKAM for all FPAs, accompanying by decreases in all pKFM. Participant P2 also decreases all pKAM, however the pKFM increases for all FPAs except during toe-out 15°. The same goes for participants P8, P9, P12, P15 and P18. All indicating that the decrease in pKAM does not necessarily mean that no extra load is exerted on the knee joint, since an increase in pKFM was found.
Highlighting the importance of assessing both moments to ensure that specific FPA modifications effectively reduce overall knee joint loading.

Previous studies, (Simic et al., 2013), have documented the effects of toeing-out on the KFM. During the 1st peak (early stance) the pKFM tends to increase (Jenkyn et al., 2008), while during the 2nd peak (late stance), KFM decreases. However, alterations in FPAs within this thesis produced variable results for KFM.
Other studies have explored the impact of adapting toe-in angles on KAM and KFM, finding no significant difference in early stance pKAM. However, applying a medial thrust gait did result in a 35% increase in pKFM. (Booij et al., 2020) Similar findings have been reported in other studies. (Walter et al., 2010) (Gerbrands et al., 2017) Comparing these studies with the findings from this thesis, it is evident that outcomes varied considerably. Some participants exhibited increases in pKFM when an increase of medial thrust is shown, while others did not. This difference could be attributed to the fact that medial thrust was measured afterwards in this study and not actively incorporated into the gait methods during testing, unlike in existing studies where different medial thrust angles were explicitly tested. Additionally, increasing gait speed (from 0.75 to 1.50 m/s) has been shown to result in a 63% increase in pKFM during late stance. (Lerner et al., 2014) Since most participants in this thesis reduced their gait speed during application of different FPAs, a decrease in KFM peak was expected. However, decreases in pKFM were only found for the toeing-out angles. While participants decreased their speed during almost all FPAs.

The standard deviations for the 1st pKFM exceeded 150%. In contrast, current studies report an 80% increase in 1st pKFM and a 107% increase in the 2nd peak. (Walter et al., 2010) Conversely, participant P13 exhibited an increase in pKFM by 300% when toeing-in 15° and a decrease of 264% was found for P20 when toeing-out 15°. pKFM was found to result in higher percentage effects compared to normal gait. However when looking at the mean differences of the 1st pKFM not in percentage but in Nm/kg, the changes appeared smaller compared to pKAM.
Including both peaks, five participant who decreased their pKAM, during their largest peak, also decreased the accompanying pKFM, however six participants who showed a decrease in pKAM, showed an increase in pKFM and resulted in not decreasing the load in the knee joint. The other five participants showed both results. Showing the effect of including both moments.

Effect of FPA on lower joint kinetics

Calculating and interpreting the hip and ankle moments presented significant challenges due to the inclusion of two different parameterization methods; measuring the moment at a specific peak and measuring the area under the curve. The comparison of these two methods across participants yielded different outcomes, as the moment could decrease at peak value but increase when assessed by the area under the curve.

The analysis of hip flexion moment revealed an overall mean decrease across all FPAs, suggesting that no negative effects were exerted on the hip in the sagittal plane. Contrary to findings in existing studies (Legrand et al., 2021), which reported an increase in peak hip flexion moment with toe-out 10°, 15°, or 20°.
A possible explanation for this overall decrease in hip flexion moment is the observed reduction in gait speed when participants applied different FPAs. This is consistent with findings in a current study (Zeni & Higginson, 2009), that indicates a correlation between a decreased hip flexion moment and a reduced gait speed. However, it is important to note that this study did not involve the application of different FPAs, making it only partially comparable to the present research.
Additionally, another study (Bokaeian et al., 2021) suggests that a reduction in medial thrust decreases hip flexion moment without significantly affecting hip adduction moment and ankle moment. Participants in this thesis who reduced both gait speed and medial thrust also demonstrated a decrease in hip flexion moment. Overall, the decrease in hip flexion moment observed in this study aligns with the desired outcome, indicating that no unwanted load was exerted on the hip joint in the sagittal plane.

The analysis of hip adduction moments revealed an increase in mean values at peak moment across all FPAs. The area under the curve only showed a mean increase for toe-in 5°. The hip adduction moment, which occurs in the frontal plane, is significantly influenced by trunk lean. According to an existing study (Mündermann et al., 2008), an increase in trunk lean (+5° to 15°) towards the investigated knee is associated with a reduction in the peak adduction moment at the hip by -57.1%. In this thesis, half of the participants increased their trunk lean during the peak for at least two of the FPAs. However, not all participants who increased their trunk lean demonstrated a corresponding decrease in hip adduction moment.
According to a current study (Legrand et al., 2021), toeing-out by 10°, 15° or 20° increased the hip adduction moment during the entire stance phase. Even when combined with a trunk lean of 5° or 10°, the hip adduction moment still increased. Comparing to this thesis, the peak value also shows an increase in the toe-out angles.
Existing studies primarily examines trunk lean increases of 5° or more, yet only participant P11 exhibited an increase in trunk lean of 5° or more, accompanied with an increase in hip adduction moment. This suggests that future research

should explore the effects of increased trunk lean as a strategy to reduce hip adduction moment during mid-stance.

The analysis of hip rotation moments revealed a mean decrease for the area under the curve, except for toe-out 15°. During the peak value, all mean values increase, except for toe-in 5°. Within this thesis, hip rotation moments decreased more with toe-in compared to toe-out.
Rotating the knee medial tends to rotate the hip internally as well, thereby increasing the hip rotation moment. (Fregly et al., 2007) (Barrios et al., 2010) (Walter et al ., 2010) However, when comparing medial thrust and toe-in across individuals, this pattern was not consistently observed. Participants who increased their medial thrust exhibited varying degrees of hip rotation, with no significant correlation identified. For future research there should be focused on gait modifications that can help decrease the hip rotation moment.

The ankle angle moment showed a mean decrease for all FPAs during peak value, conversely the area under the curve had a mean increase for all FPAs except for toe-in 5°. This increase could be attributed to participants experiencing increased stiffness in their ankle joints when altering their gait. Some participants reported in the questionnaire that they felt stiffer ankle joints and experienced improper ankle roll-off when modifying their FPA.
Additionally, an imbalance caused by a narrower step width can displace the center of mass, leading to increased ankle moments. (Anderson et al., 2018) This could explain the increase in toe-in 5° when measuring the area under the curve.
A current study (Legrand et al., 2021) suggests that toeing-out by 10°, 15°, or 20° generally decreases the ankle moment in both early and late stance. This could explain the observed decrease in mean values for the larger toe-out angle, however only for the peak value.

Overall it is noticed that the hip flexion moment resulted in a mean decrease for both parameterization methods. The hip adduction, hip rotation, and ankle moment all showed overall an increase during peak values and an overal decrease when measuring the area under the curve. Where hip adduction moment contains a slightly higher increase compared to hip rotation moment. All indicating that the maximum peak load is higher and more important to focus on compared to cumulative load.

Parameterization methods lower joint kinetics

The parameterization methods used to assess moments in the hip and ankle joint, yield different insights. Calculating the moment at peak value provides an indication of the maximum load experienced by the joint at a specific moment in time, which is likely during mid-stance, when the hip or ankle joint is expected to bear the greatest load. This can help to understand the demands of the joint during peak intensity
In contrast, examining the total area under the curve offers an insight on the cumulative load on the hip or ankle joint throughout the entire stance phase. This approach includes the impulse, which accounts for both the magnitude and duration of loading. Understanding cumulative load is crucial for assessing the total exposure of a joint to stress over time, which is important for analyzing the repetitive loading that contributes to the degradation of articular cartilage.

Current studies (Maly et al., 2013) compared cumulative load and peak load between healthy participants and participants with OA. It showed that cumulative load measurements are more effective in distinguishing between these groups. This is because cumulative load measurements incorporate more factors such as impulse and loading repetition. Therefore, depending on the objectives of the analysis, both parameterization methods provide valuable, yet distinct, insights into joint loading and potential cartilage degeneration.

Effect of FPA on spatiotemporal and kinematic gait parameters

The next focus is on gait parameters. As expected, nearly all participants decreased their gait speed when changing the FPA. Notably, only participants P7 and P13 demonstrated an increase in gait speed across all FPAs, while P10 increased the speed for three out of four FPAs. Participants P1 and P16 increased their gait speed for two and one FPAs, respectively. All other participants decreased the speed across all FPAs. Comparing the mean gait speeds for different FPAs with normal gait, there was a decrease of 13.33%, 12.32%, 14.35%, and 18.54 % for toe-in 5°, toe-in 15°, toe-out 5°, and toe-out 15° of, respectively. This suggests that altering the FPA generally decreases the gait speed, which subsequently decreases the KAM. (Khan et al., 2017)

Examining the stride length during the FPAs, ten out of fifteen participants reduced their stride length across all FPAs. Participant P2 increased stride length during all FPAs, while the remaining four participants exhibited both increases and decreases. When calculating the mean values, all FPAs showed a mean decrease in stride length compared to normal gait, with reductions of 11.06%, 16.60%, 15.65%, and 17.54% for toe-in 5°, toe-in 15°, toe-out 5°, and toe-out

15°, respectively.
Previous studies have explored the correlation between stride length and joint kinetics. One study, (Bennour et al., 2018), found that increasing the stride length by 0.14 m, while maintaining gait speed and without altering FPA, led to an increase in both pKAM and pKFM across the entire group. Another study (Ulrich et al., 2023) did not observe an overall decrease in pKAM when shortening the stride length (-0.10 to -0.15m). However, at individual level 1/3 of the participants did experience a reduction pKAM with a shorter stride length, without an increase in pKFM. A third study (Edd et al., 2020) did found that shortening the stride length (-0.14 m) decreased pKAM for half of the participants.
Comparing the studies to this thesis, 20% of participants who exhibited a reduction in stride length across all FPAs also demonstrated a decrease in pKAM without an increase in pKFM. For three other participants this only appeared for one or two FPAs. However, the overall impact of changing the FPA as a group led to a reduction in stride length.

Comparing the mean values for the step width, all FPAs show a wider step width compared to normal gait; 68.81%, 76.73%, 20.02%, and 13.58% for toe-in 5°, toe-in 15°, toe-out 5°, and toe-out 15°, respectively. As expected a wider step width is found during toeing-in. Current studies, (Bennett et al., 2017) (Booij et al., 2020), focused on the combination of toe-in 10° and step width (+26% from normal step width), and decreased the 1st pKAM by 38%. A wider step width mostly decreases the 1st pKAM, but another study also decreased the 2nd pKAM. (Favre et al., 2016) It is also found in current studies that a bigger step width increases the pKFM. (Bennour et al., 2018) (Edd et al., 2020) Questioning whether a wider step width (+ 0.16 m) decreases the overall load in the knee compartment, or not due to pKFM.
Within this study, one participant decreased the step width for all FPAs, eight participants increased step width for all FPAs. The other participants showed increases and decreases within the FPAs.

Calculating the trunk lean within this thesis revealed a mean decrease of 5.22% and 5.72% for toe-in 5° and toe-out 15°, respectively. While an increase of 0.47% and 1.64% was found for toe-in 15° and toe-out 5° compared to normal gait.
Previous studies (Mündermann et al., 2008) have shown that increasing the trunk lean by 10° to 15° can reduce the pKAM on average by 65% in healthy participants. However, that study exclusively altered trunk lean without modifying the FPA. Conversely, this thesis primarily examines the impact of changes in FPA on trunk lean. Another study (Shull et al., 2011) investigated the combined effect of toeing-in (13-25°) and trunk lean (7-17°), all but one participant decreased the 1st pKAM by at least 30%. Additionally, increasing trunk lean decreases both the pKAM and pKFM. (Lindsey et al., 2021)
This correlation between trunk lean and pKFM was not consistently observed in this thesis. Changing the FPA resulted in minimal alterations in trunk lean, typically below 5°, underscoring the potential of this parameter if participants consciously adjust it. Three participants increased trunk lean for all FPAs, four participants decreased trunk lean for all FPAs, and the remaining participants exhibited mixed changes.

Regarding medial thrust, the mean values showed a reduction of 318.86% and 426.21% for toe-in 5° and toe-out 5°, respectively. While medial thrust increased 105.64% and 77.63% for toe-in 15° and toe-out 15°, respectively. Medial thrust refers to the inward movement of the knee joint, and an increase is expected to correlate with toeing-in. (Lindsey et al., 2021)
One study (Bokaeian et al., 2021) proves that an increase in medial thrust can decrease the pKAM (by 18%) without significantly affecting pKFM. In this thesis, larger angles for toeing-in and toeing-out showed an increase in medial thrust, accompanied by a decrease in pKAM and pKFM.
Medial thrust remains a relatively underexplored gait parameter. Most studies either focus on a single participant (Fregly et al., 2007) (Fregly et al., 2009) or examine medial thrust without considering FPA. This thesis highlights significant variations in medial thrust with different FPAs compared to normal gait, yet the precise impact on pKAM requires further investigation.

The spatiotemporal parameters exhibited different changes among participants when altering their FPA. Notably, eleven participants increased trunk lean when applying at least one FPA. Of these, eight participants also exhibited an increase in medial thrust during the same FPA, suggesting a possible correlation between trunk lean and medial thrust. However, this pattern was not observed in all participants, indicating variability in individuals.

8.1 Limitations

This study included only healthy participants, which may have influenced the outcomes. One study (Simic et al., 2013) indicates that individuals without KOA can adopt greater degrees of toe-in and toe-out compared to those with KOA, highlighting a difference in gait adaptations between the two groups. Therefore, future studies should include participants with KOA to provide a more comprehensive understanding of the effects of FPA.

Initially, this thesis aimed to measure exact angles of 5° and 15° toe-in and toe-out with a range for the sensors of ±1°. However, pilot testing revealed this range was too narrow, making it difficult to even take one step within the desired range. A minimum range of ±2.5° was found necessary for participants to take multiple steps within the range, leading to adjustments in the targeted FPAs. One study (Shull et al., 2011) reported similar challenges. Resulting in revising the small angle range to 5° and 10°, and the larger angle range to 18° and 23° degrees. The larger angle was increased to have a significant difference between the small and a large angle.
Existing studies (Lynn et al., 2008) indicate that healthy individuals can comfortably achieve a FPA of up to 40°. Whereas people with KOA can comfortably increase their FPA to 18°. (Guo et al., 2007) Supporting the decision to increase the larger angle to the value mentioned above.

Limitations KneeWear product

The Xsens Dot sensor encountered several challenges during testing, primarily due to electromagnetic field interferences of the sensor within the test facilities. This interference occasionally led to the sensor registering deviations in the FPA. Thereby possibly affecting the accuracy of the results. The FPA was continuously monitored during testing using this sensor to ensure participants executed sufficient correct steps for the analysis. However, after testing, the FPA was measured with Matlab, revealing that some participants had little correct steps, despite the sensor indicating otherwise during the test. Although the sensor was recalibrated frequently, errors persisted. A potential solution can be to use an alternative sensor or an updated measuring system.

Another issue that occurred during testing was that participants often reduced their gait speed and their stride length when modifying their gait. This resulted in frequently both feet landing on the same force plate, making these steps unusable for analysis. This should be monitored better during future research.

Analysis

The analysis in this thesis was conducted on a small sample size (n = 15), which may impact the reliability of the results. A small sample size constrains the alibility to identify statistically significant correlations. Although the current statistics did not reveal any correlations between gait parameters and FPAs, existing studies suggests that such correlations could be expected. The difference can stem from this thesis focusing on altering the FPA, rather than modifying gait parameters, which is more common in existing studies.
Furthermore, identifying correlations between FPA, KAM, and gait parameters, involves more complex statistical analyses than within the scope of this thesis, especially given the sample size. Future research with a larger sample size and more robust statistical methods would be necessary to draw more definitive conclusions.

8.2 Recommendations

Several participants reported difficulty in distinguishing between medial and lateral vibrations on the malleoli from the haptic feedback system, particularly during prolonged walking sessions. Some participants suggested incorporating varying vibration intensities to indicate whether a significant adjustment or just a minor adjustment in FPA is required. This modification could potentially enhance the participants' ability to adopt the desired FPA more quickly. Additionally, participants recommended to modify the vibrations so that they only occur when the foot is in contact with the ground.

Exploring alternative feedback systems, such as auditory or visual cues could also be beneficial. These systems might reduce the learning time for participants and possibly solve the issues participants had with the current feedback system. During testing, most participants walked with their heads down to focus on their toes, which affected their posture. Implementing visual feedback, such as video display or a mirror at the end of the walkway, could help participants maintain a more natural posture while walking.

One existing study (Chehab et al., 2014) suggests that KFM may continue to increase medial load in the knee joint over the years, and potentially predict disease progression in the future. Another study (Chang et al., 2015) that lasted two years, showed the complexity and uncertainty surrounding the exact influence of KFM. Future research should investigate whether KFM is a reliable predictor of disease progression and whether it continues to increase the load in the knee joint. Additionally, it should be researched whether a significant reduction in pKAM can offset potential increases in pKFM. Highlighting the importance of including KFM in future research to provide a more comprehensive understanding of knee joint loadings and mechanics.

For future research, it is recommended to reconsider the experimental set-up. The use of a catwalk in this study posed challenges for data collection, as participants had to interruption their walking to make a 180-degree turn at the end of the catwalk. Additionally, participants had to stand still for five to ten seconds to allow the Xsens DOT sensor to recalibrate each time the walking direction changed. Consequently, participants were able to set approximately ten steps before standing still and restarting. This negatively influenced the focus of the participant and probably increased the learning time. Using a treadmill could eliminate these interruptions and the need for sensor recalibration, thereby improving the learning curve of the participants.

The current test set-up included three force plates, resulting in only three steps per each walking direction to analyze. Using integrated force plates throughout the entire walking direction would enable the collection of data over a longer period, allowing to take the average during the entire two minutes. Existing literature often analyzes data from the final ten steps of a two-minute walking session.

Parameterization methods lower joint kinetics

Analyzing the calculation methods for the hip and ankle moments, a third method is interesting to include. One study (Legrand et al., 2021) examines parts of the stance phase to better understand joint moments. Different segments of the stance phase yield varying results. Early stance phase (0%-10%) decreases the moments in the hip adduction moment and the ankle moment. The second part of the stance phase (20%-40%) decreases the hip adduction moment and increases the ankle moment. Mid-stance phase (40%-60%) increases hip adduction and ankle moment. Late stance phase (80%-90%) decreases the external moment at the hip and ankle. While the end of the stance phase (90%-100%) increases hip and ankle moments.
This suggests a third possible calculation method that dissects the stance phase into segments. This method not only captures the differences between various parts of the stance phase, but also includes the impulse and the load duration.

Spatiotemporal and kinematic gait parameters

For future research it is advised to selectively focusing on specific gait parameters beyond the FPA, since all potentially influence the KAM. Maintaining constant values for some of these gait parameters could provide clearer insights into the isolated effects of FPA or other variables.
For instance, drawing a line on the ground for the participants to stay on, can eliminate the difference is step width. Additionally, wearing something around the back of the participant can eliminate the trunk lean. Conducting experiments on a treadmill allows for the exclusion of gait speed as a variable. This is particularly important because gait speed influences the duration of the gait cycle, and thus affects the results, especially the impulse. Existing studies, (Meinders et al., 2021) (Gerbrands et al., 2014), correct for gait speed to isolate the effects on pKAM. However, a fixed walking speed is not achievable for all individuals, especially for those with KOA, who often have altered gait patterns. This can influence the moments and the ease of adopting a new gait modification after training.
Future research should focus on isolating or controlling gait parameters to provide more precise insights into their effects on KAM.

Training time

This research focuses solely on the immediate effects of FPA following a single testing session, with participants practicing each modification for two minutes. However, it is expected that longer and repeated training sessions could result in more significant reductions in pKAM and pKFM. Existing studies have required participants to return for multiple sessions to analyze the impact of gait modification on KAM and pain symptoms. Returning once a week or every other week for a new training session. After six to ten weeks of repeated training, an improvement of ease of gait alteration is observed within these studies. (Shull, Silder, et al., 2013) (Hunt & Takacs, 2014) Moreover, while feedback is beneficial in facilitating gait changes, research indicates that although feedback assists in improving the gait change, it is not necessary for the whole training time to train with feedback. Reducing or even eliminating the feedback after a few training sessions still resulted in pKAM reduction. (Shull, Silder, et al., 2013)

Include impulse KAM

This thesis measures the KAM and KFM to asses the load on the knee joint. However, a few current studies also include the KAM impulse. The KAM impulse, which represents the area under the curve of the KAM over time, is thought to be an important indicator of disease progression. Existing studies (Chang et al., 2015) demonstrated that the KAM impulse can be a valuable predictor of cartilage thickness loss over a two-year period. Additionally, several studies have found that the KAM impulse tends to decrease more significantly then pKAM during testing. (Edd et al., 2020) (Bennet et al., 2017) (Favre et al., 2016) Additionally, these studies focused on the influence of the step width on the KAM impulse, revealing that a shorter step width reduces the KAM impulse. (Ulrich et al., 2023) Conversely, a lower gait speed has been shown to increase the KAM impulse. (Robbins & Maly, 2009)

The KAM impulse is a newly factor, important to possibly give insights on the predictability of cartilage loss over the years. Recommending to focus on for future research, mainly for studies that lasts multiple years since the impulse may serve as a valuable predictor of future joint health over extended periods.

9. Conclusion

This thesis focused on the haptic feedback system to answer the following question:

'How does altering the foot progression angle affect lower limb kinetics, spatiotemporal and kinematic gait parameters when using a haptic feedback system?'

The applied haptic feedback system is very promising, participants found it easy in use and did not exhibit joint pain. However, the vibrations on the medial and lateral side of the malleoli became confusing after a prolonged time. Additionally, the haptic feedback appeared every second, what also confused the users after prolonged walking. Both important feedback to use for improving the device.

The change in FPA affects both the lower limb kinetics, and the gait parameters. Most participants decreased their overall gait speed, step width and stride length. These overall reductions in spatiotemporal parameters are also expected to decrease pKAM. The trunk lean and medial thrust differed between participants whether it increased or decreased, and showed diverse effects on the pKAM. The effects of the different gait parameters that were found in current studies were not all confirmed within this thesis. The main reason for this is that wihtin this thesis the change in gait parameters occurs when changing the FPA, while current studies focus on altering these parameters during testing.

The lower joint kinetics show an overal decreases in hip flexion moment. The hip rotation, hip adduction, and ankle moment all show an overall increase during peak value and an overall decrease when measuring the area under the curve. This indicates that the main focus to reduce these moments should be on reducing the peak value, the maximum load experienced by the joint at a specific moment in time.

This thesis also highlighted the importance of a personalized approach. Comparing overal values with individual values sometimes indicated different results. Each participant reacts differently to changes in FPA and the effect on the lower joint kinetics and gait parameters. Additionally, it is important to remember the main focus, decreasing the pain for the people with KOA to increase their quality of life.

Part V
References & Appendices

05

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Appendix A: Files ethics committee

Delft University of Technology
HUMAN RESEARCH ETHICS
INFORMED CONSENT

Welcome,

You are being invited to participate in a research study titled 'Evaluation of haptic feedback and application of different FPA to the knee adduction moment'. This study is being done by Yvette Keij from the TU Delft as master thesis.

The purpose of this research study is to measure the moment in the different joints (ankle, knee and hip) to see the effect of changing your foot progression angle. Your foot progression angle measures whether your toes are rotated more to the outside or rotated more to the inside, and will take you approximately 120 minutes to complete. The data will be used for the master thesis. We will be asking you to walk in five different ways. Your 'normal' way of walking, and rotating your foot in four different ways to the outside and inside while wearing the feedback device of Elitac Wearables.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by not writing any names down, the only personal data that is needed is gender, age and weight. After this each participant will be assigned a number to keep the data collection confidential but applied to the correct participant. After obtaining and processing the data in the thesis, all personal data will be deleted from the project drive. The data that is included in the thesis that will be published on the repository of TU Delft, will be anonymized.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. When no questions arise, I ask you kindly to fill in the survey below.

Thank you in advance for your participation.

Kind regards,
Yvette Keij

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION	☐	☐
1. I have read and understood the study information dated ………………, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: a video recording of me walking back and forth, this video recording will be saved on the drive of the TU Delft that is only available for people who are accepted to have access to this. Besides for personal data the following are given: gender, age and weight.	☐	☐
4. I understand that no compensation will be provided for participants in this study.	☐	☐
5. I understand that the study will end as soon as the experiment is over, this will approximately take 120 minutes of my time.	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves collecting specific personally identifiable information (PII) such as video images, and associated personally identifiable research data (PIRD) such as gender, age, weight with the potential risk of my identity being revealed.	☐	☐
7. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach; secure the video images on the drive of TU Delft that is only available with access, don't write down any names of the participants, only wright down gender, age and weight and give participants a number, and wright this down in a different document then where the video images are saved.	☐	☐
8. I understand that personal information collected about me that can identify me, such as video images, will not be shared beyond the study team.	☐	☐
9. I understand that the (identifiable) personal data I provide will be destroyed one month after the thesis is written (approximately July 2024).	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
10. I understand that after the research study the de-identified information I provide will be used for further research on this subject for students at TU Delft only.	☐	☐
11. I give permission for the data that is not identifiable to be included in the thesis that eventually will be published in the repository of TU Delft, and I understand that this access is open.	☐	☐

Questionnaire knee osteoarthritis

Name: ....

1. Did you find the feedback system around the ankle comfortable or uncomfortable?

2. How quickly did you understand the feedback system? Did it feel like you mastered walking at the required angle with your feet quickly?

3. Was the gait adaptation with the different angles comfortable, or did it cause pain in other joints?

4. Do you have any additional comments about the feedback system and walking at the required angles?

Appendix B: Values parameters

Excluding reason for the data:

Participant	Gait	Reason
P3	Static	Does not open in OpenSim
P4	All	All force plates incorrect calibrated
P5	All	All force plates incorrect calibrated
P6	All	All force plates incorrect calibrated
P8	Toe-in 15	Always two feet on each force plate
P9	Toe-in 15	Always two feet on each force plate
P11	Toe-out 15	Always two feet on each force plate
P15	Toe-out 15	Does not open
P16	Toe-in 5	Every right foot on the middle force plate which is incorrect calibrated
P17	All	Every right foot on the middle force plate which is incorrect calibrated
P19	Toe-out 5	Always two feet on each force plate
P20	Toe-out 5	Incorrect graph

Exact Foot Progression Angle's

The exact foot progression angle that the participants walk during their normal gait, and during the different gait modifications. Besides the number of good steps are written down. The good steps are counted that fall within the range, for the small angle this is between 5° and 10°, for the big angle this is between 18° and 23°. Some gait modifications are not in the exact wanted range, this is due to the fact that the good steps were unusable. Either the participant walked with two feet on the force plate, the good step was next to the force plates, or the calibration was done incorrectly resulting in the ground reaction force not being directly below the foot.

	Normal gait (°)	Toe-in 5 (°)		Toe-in 15 (°)		Toe-out 5 (°)		Toe-out 15 (°)	
P1	-2	-1.5	5x	-10	2x	9.8	6x	20.7	15x
P2	4.2	-7.3	17x	-17.9	6x	9.5	14x	21	20x
P7	-1.04	-8.7	21x	-22.5	21x	9.9	7x	21	12x
P8	-9	-5.6	5x	-	-	11.5	5x	21	7x
P9	-6.5	-0.5	8x	-	-	7.8	13x	20.5	6x
P10	-3.6	-7.5	15x	-17.5	5x	6.5	11x	20	8x
P11	-8.5	-3.1	5x	-12	12x	12.5	7x	-	-
P12	-2.5	-5.2	15x	-21	16x	9	14x	18	7x
P13	-5.5	-3.3	4x	-17.1	8x	9	4x	25	6x
P14	10	-6.4	7x	-12	2x	16	0x	33	6x
P15	-13	-7.5	24x	-7.2	1x	5.7	2x	-	-
P16	-12	-	-	-12	2x	13	3x	23	3x
P18	6	-9	7x	-20	2x	7	9x	22	8x
P19	1.5	-6.4	3x	-11	1x	-	-	21	8x
P20	-5.3	-7.5	11	-15	7x	10	11x	20.5	7x

Gait speed per participant per gait modification

	Normal gait (m/s)	Toe-in 5 (m/s)	Toe-in 15 (m/s)	Toe-out 5 (m/s)	Toe-out 15 (m/s)
P1	1.20	1.19	1.23	1.24	1.20
P2	1.27	1.26	1.24	1.25	1.26
P7	1.04	1.15	1.25	1.11	1.08
P8	1.54	0.67	-	0.99	0.98
P9	1.12	0.95	-	0.96	0.95
P10	0.88	0.88	1.1	1.00	0.97
P11	0.85	0.75	0.76	0.75	-
P12	1.55	1.20	1.06	1.51	1.16
P13	1.06	1.14	1.11	1.18	1.22
P14	1.15	0.70	0.71	0.72	0.66
P15	1.48	1.36	1.42	1.16	-
P16	1.00	-	0.76	1.06	0.89
P18	1.22	0.96	0.95	0.93	1.18
P19	0.75	0.69	0.74	-	0.70
P20	0.99	0.78	0.79	0.80	0.85
Mean	1.12 ± 0.24	0.98 ± 0.23	0.99 ± 0.24	0.97 ± 0.22	0.93 ± 0.19

Stride length in meters per participant per gait adaptation

	Normal gait (m)	Toe-in 5 (m)	Toe-in 15 (m)	Toe-out 5 (m)	Toe-out 15 (m)
P1	1.29	1.18	1.17	1.23	1.26
P2	1.15	1.23	1.18	1.19	1.2
P7	1.17	1.14	1.17	1.32	1.11
P8	1.44	0.97	-	1.15	1.03
P9	1.33	1.04	-	1.06	0.98
P10	1.17	1.18	1.24	1.0	1.02
P11	1.1	0.95	0.97	0.92	-
P12	1.43	1.28	1.20	1.35	1.26
P13	1.24	1.24	1.10	1.20	1.22
P14	1.20	0.96	0.97	0.96	0.88
P15	1.39	1.33	1.42	1.35	-
P16	1.15	-	1.10	1.26	1.23
P18	1.30	1.14	1.17	0.63	1.24
P19	1.04	0.88	0.95	-	0.95
P20	1.25	1.06	0.95	1.10	1.00
Mean	1.24 ± 0.12	1.11 ± 0.13	1.05 ± 0.14	1.06 ± 0.19	1.04 ± 0.13

Step width in millimeters per participant per gait adaptation

	Normal gait cm)	Toe-in 5 (cm)	Toe-in 15 (cm)	Toe-out 5 (cm)	Toe-out 15 (cm)
P1	-	-	-	-	-
P2	-	-	-	-	-
P7	7.3	18.6	27.0	3.6	3.6
P8	4.6	19.0	-	6.9	9.0
P9	11.1	17.0	-	14.8	10.8
P10	8.0	11.3	13.4	10.0	10.4
P11	14.6	11.3	10.5	9.1	-
P12	4.8	13.8	22.3	9.8	10.6
P13	10.9	13.3	22.4	12.4	8.0
P14	5.9	7.1	7.8	7.0	6.2
P15	8.1	9.0	13.8	6.4	-
P16	4.0	-	13.5	8.7	9.1
P18	5.9	13.5	14.1	8.8	7.9
P19	5.0	15.7	16.5	-	5.5
P20	7.9	20.6	25.2	13.2	14.1
Mean	7.55 ± 3.11	15.47 ± 4.46	16.95 ± 6.57	9.23 ± 3.27	8.65 ± 3.05

Trunk lean angle in degrees

	Static (°)	Normal gait (°)	Toe-in 5 (°)	Toe-in 15 (°)	Toe-out 5 (°)	Toe-out 15 (°)
P1	4.46	8.39	8.22	6.77	7.58	6.76
P2	5.13	9.60	10.61	10.23	11.01	8.91
P7	3.08	8.46	8.17	9.54	7.98	5.84
P8	4.38	7.70	3.86	-	4.37	4.33
P9	3.97	12.41	8.50	-	12.02	9.11
P10	5.55	8.59	6.39	9.72	7.29	7.41
P11	6.96	9.42	13.77	15.51	15.60	-
P12	4.29	7.88	8.46	6.61	9.08	6.94
P13	3.69	7.95	6.54	6.01	7.55	7.59
P14	3.04	6.59	4.89	3.09	3.30	9.60
P15	5.98	10.95	11.23	9.93	11.03	-
P16	5.40	9.34	-	8.82	9.05	12.70
P18	2.40	2.77	4.16	4.53	4.33	4.23
P19	5.64	7.42	7.40	7.77	-	9.11
P20	4.19	9.29	10.18	11.81	10.09	11.19
Mean	4.54 ± 1.24	8.45 ± 2.11	8.02 ± 2.88	8.49 ± 3.24	8.59 ± 3.31	7.98 ± 2.51

Medial thrust gait

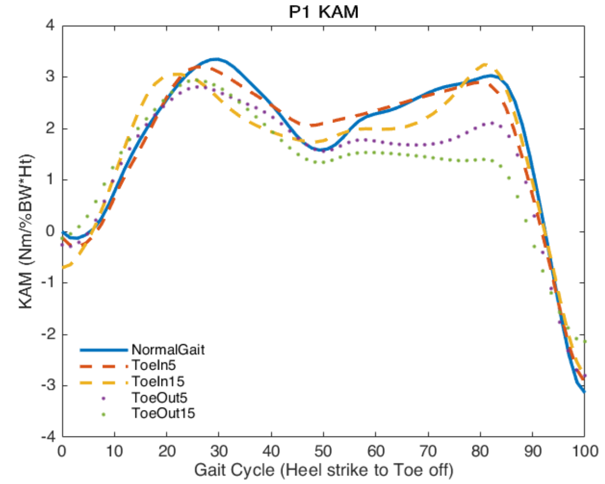
The positive values the knee is rotated away from the midline, for negative values the knee is rotated towards the midline (inward).

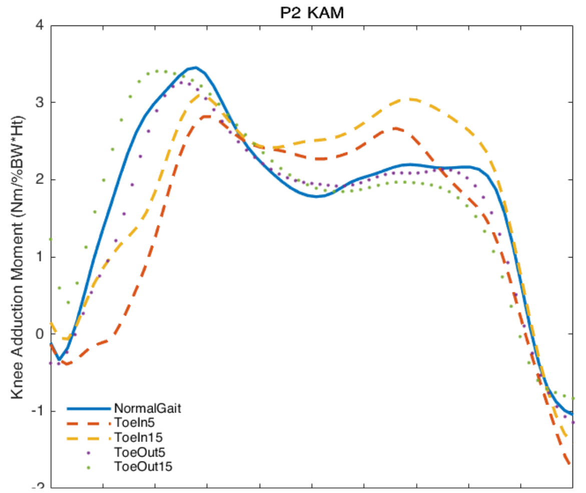
	Normal gait cm)	Toe-in 5 (cm)	Toe-in 15 (cm)	Toe-out 5 (cm)	Toe-out 15 (cm)
P1	30.32	6.4	-6.68	-8.94	26.85
P2	-3.96	-0.51	-7.13	-24.63	18.42
P7	7.72	-8.10	16.80	7.53	0.64
P8	-19.91	-14.47	-	-15.85	1.45
P9	-18.22	28.29	-	18.91	20.37
P10	1.70	-5.6	15.57	-10	-7.14
P11	25.77	-9.93	17.96	-5.73	-
P12	-10.87	2.00	-1.33	0.87	16.77
P13	-7.54	4.16	11.24	-2.95	-7.2
P14	-0.06	-5.9	13.90	3.95	-6.48
P15	16.69	14.17	7.19	20.7	-
P16	5.86	-	20.01	-9.96	-15.56
P18	15.89	-4.26	1.87	-11.00	-3.03
P19	7.07	-9.27	-5.08	-	-2.79
P20	-16.35	-9.26	11.36	25.58	24.68
Mean	2.27 ± 15.98	-0.52 ± 10.97	7.36 ± 9.90	-0.82 ± 14.78	5.15 ± 14.54

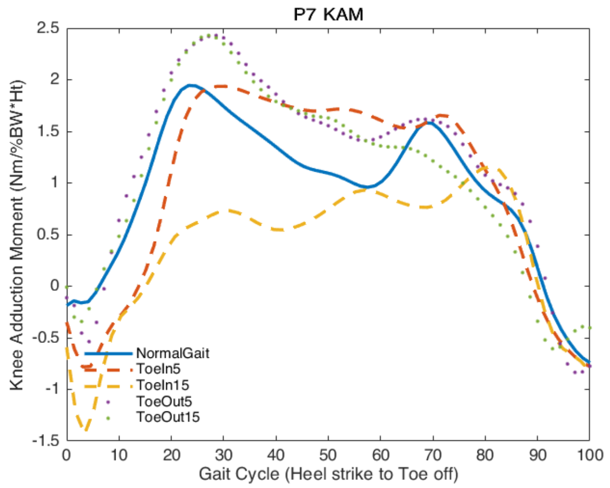
Appendix C: Graphs moments

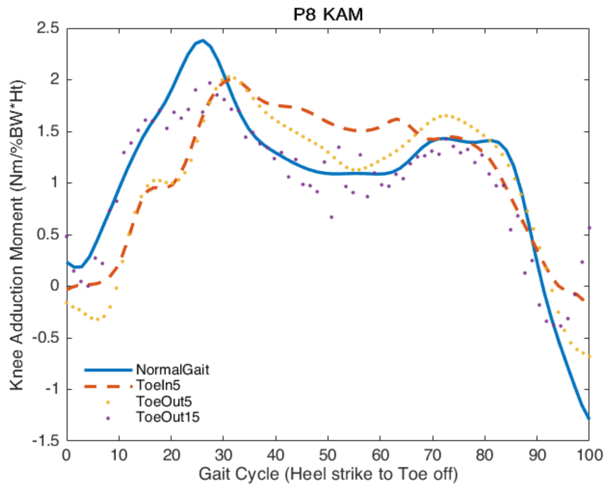
Graphs KAM

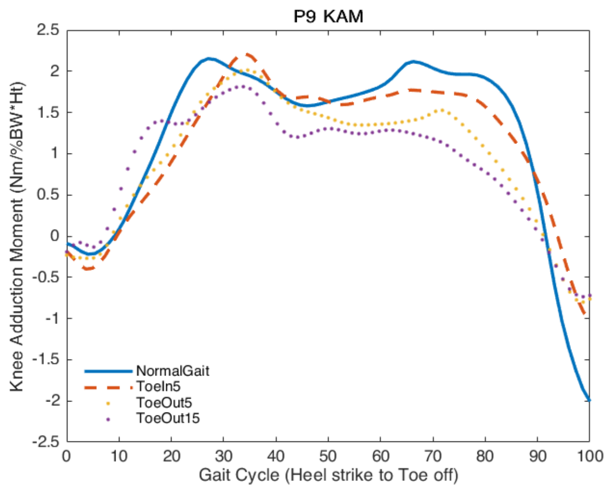
The y-axes represents moments normalize by percentage of body weight times height, while the x-axes depict the stance phase of the gait cycle from heel strike to toe-off.

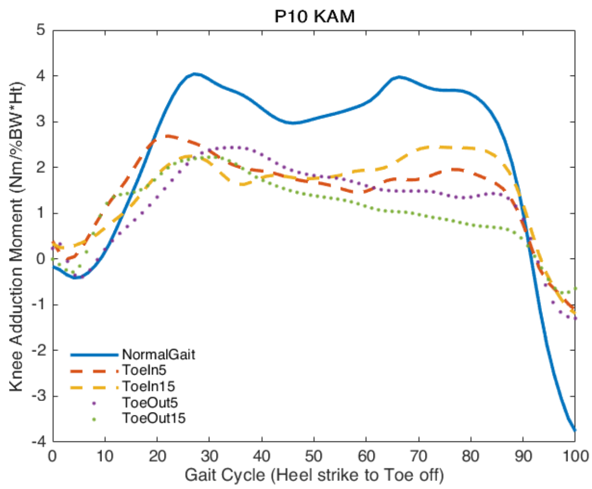


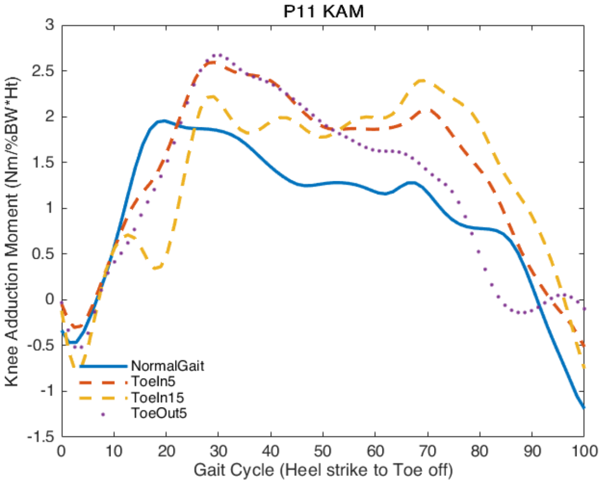


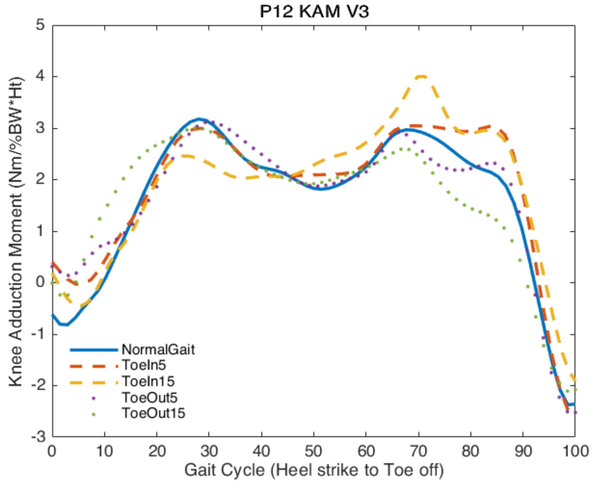


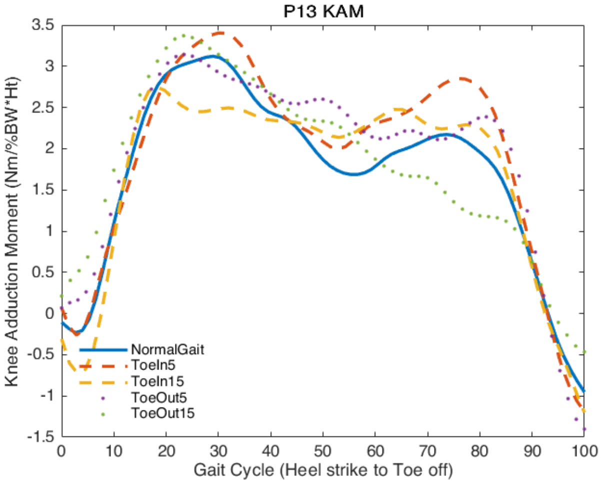


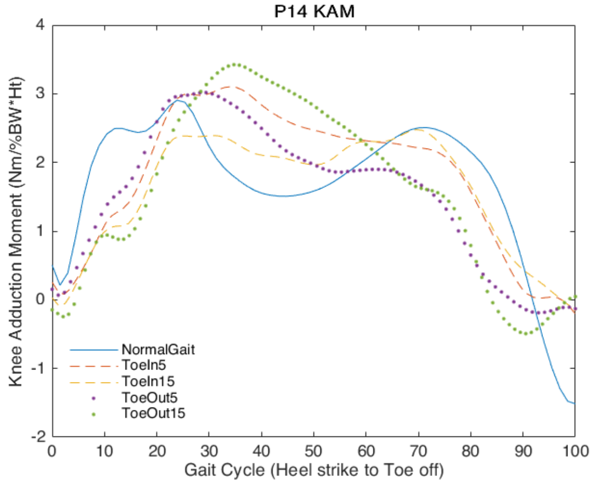


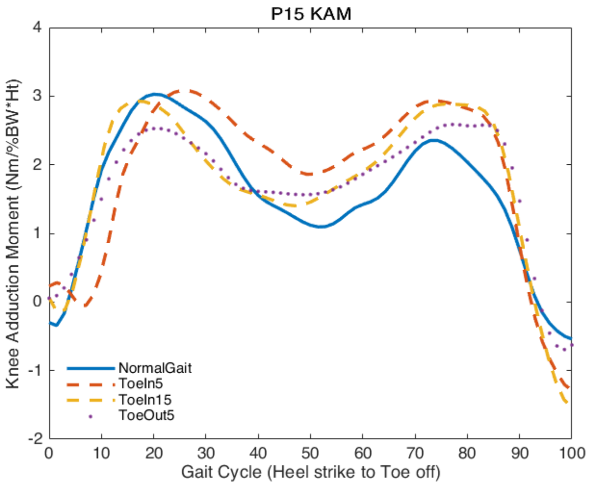


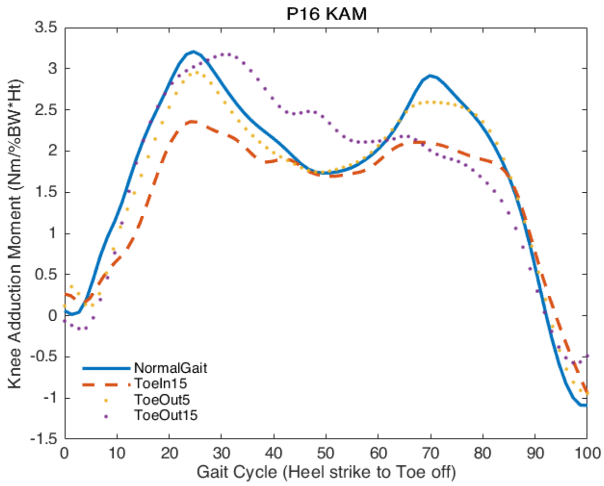

P11 KAM
Knee Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5

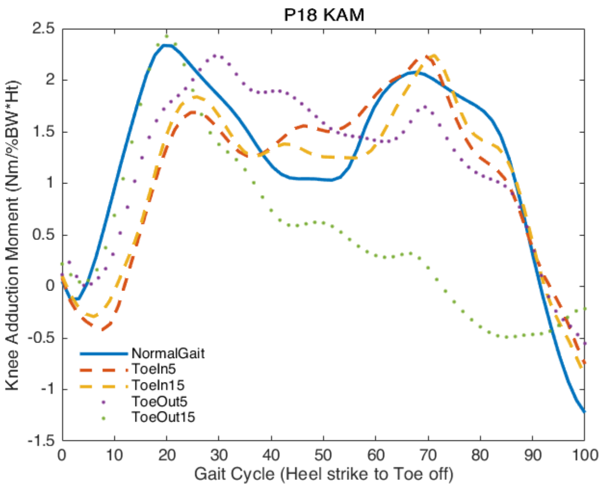

P12 KAM V3
Knee Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

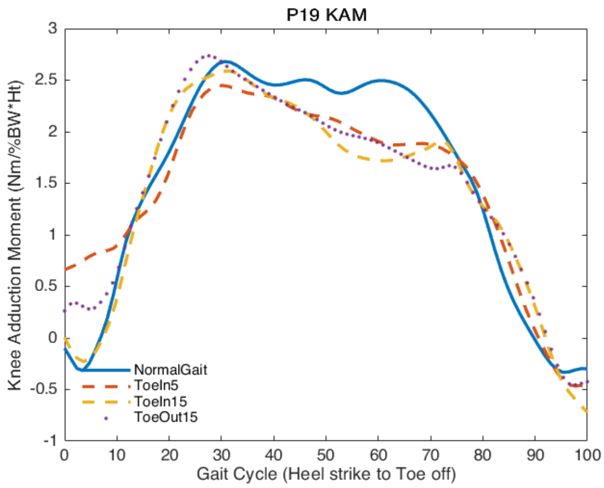

P13 KAM
Knee Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

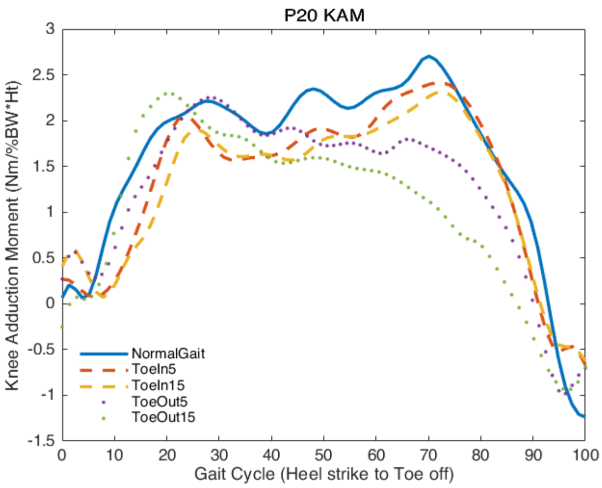

P14 KAM
Knee Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15


P15 KAM
Knee Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5


P16 KAM
Knee Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn15
ToeOut5
ToeOut15


P18 KAM
Knee Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15


P19 KAM
Knee Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut15

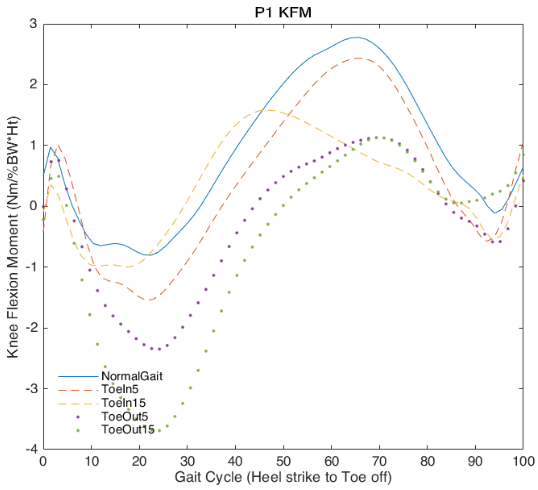


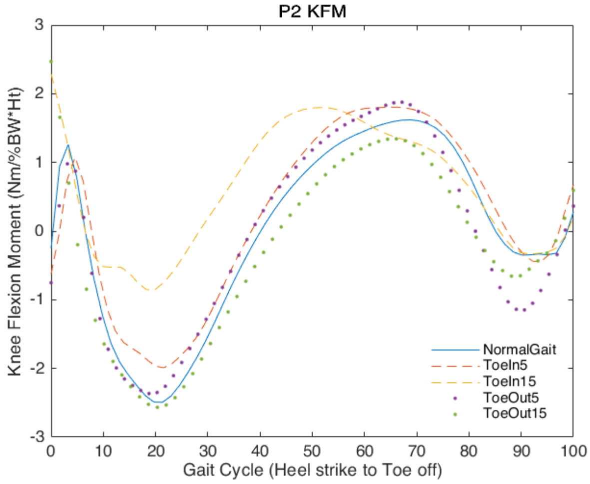
	1st peak KAM				2nd peak KAM			
	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)
P1	-4.2	-8.7	-15.9	-12.0	-4.3	6.9	-30.7	-54.1
P2	-18.3	-10.4	-5.5	-1.4	21.5	38.8	-2.7	-11.0
P7	-1.0	-62.4	24.7	25.3	5.7	-26.1	3.2	-15.3
P8	-16.0	-	-14.7	-17.2	0.7	-	15.4	-5.6
P9	2.8	-	-6.1	-15.9	-16.6	-	-27.5	-40.3
P10	-33.9	-44.3	-39.9	-45.0	-46.9	-33.5	-59.7	-72.2
P11	32.8	13.8	36.9	-	62.5	86.7	24.2	-
P12	-5.4	-22.7	-1.9	-5.4	2.7	35.1	-3.0	-12.8
P13	9.0	-11.9	0.6	8.0	31.3	5.5	-12.4	-24.0
P14	2.7	-18.2	3.4	17.5	-11.2	-1.2	-27.5	-37.8
P15	1.7	-3.6	-16.8	-	24.7	22.1	10.2	-
P16	-	-26.5	-8.1	-1.2	-	-28.1	-11.3	-25.3
P18	-27.8	-21.4	-4.7	3.8	8.2	7.7	-16.3	-84.6
P19	-9.0	-3.4	-	2.2	-24.1	-23.3	-	-32.9
P20	-7.2	-14.0	1.8	3.6	-10.7	-14.4	-33.3	-49.3
Mean ± SD (%)	-5.3 ± 17.8	-17.98 ± 18.39	-3.30 ± 17.60	-2.88 ± 18.10	3.11 ± 25.71	5.86 ± 33.94	-12.25 ± 22.87	-36.33 ± 23.57
Mean ± SD (Nm/kg)	2.66 ± 0.58	2.50 ± 0.65	2.77 ± 0.45	2.68 ± 0.56	2.26 ± 0.54	2.65 ± 0.71	1.96 ± 0.44	1.48 ± 0.56

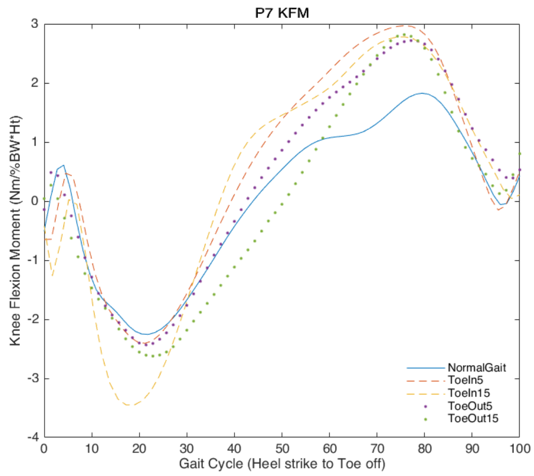
Table: Values for KAM

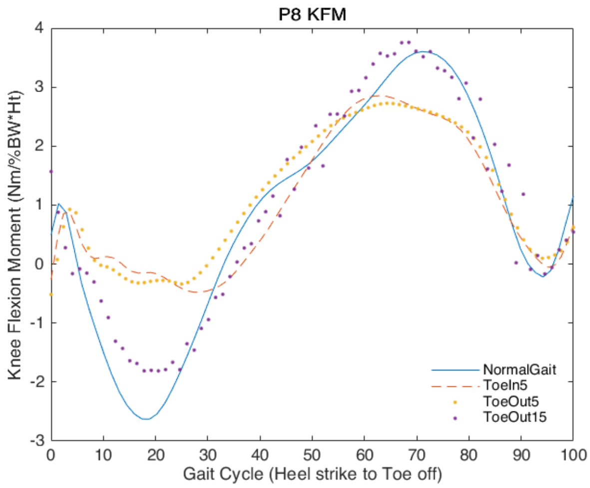
Table with the different FPAs and which pKAM decreases for what angle, expressed in percentages compared to normal gait. It is expected that toe-in decreases the 1st peak and toe-out decreases the 2nd peak. The percentages below 5% are marked grey, since a reduction in pKAM of 5% or more is, according to literature (Shimada et al., 2006), associated with improved knee moment and pain.
The lowest two rows show the mean value per FPA in percentage, and the mean value per FPA in Nm/kg.

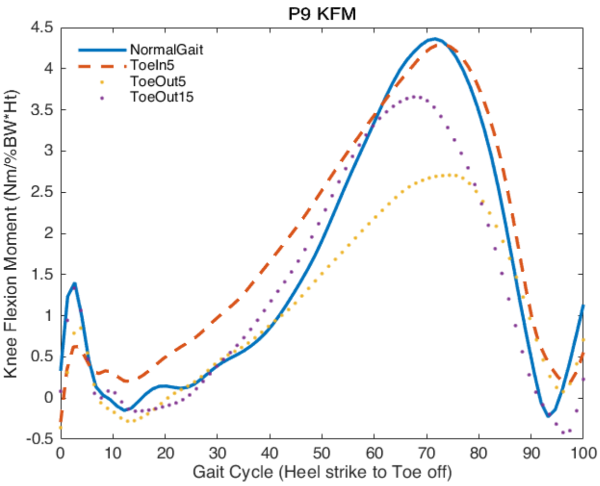
Graphs of knee flexion moment

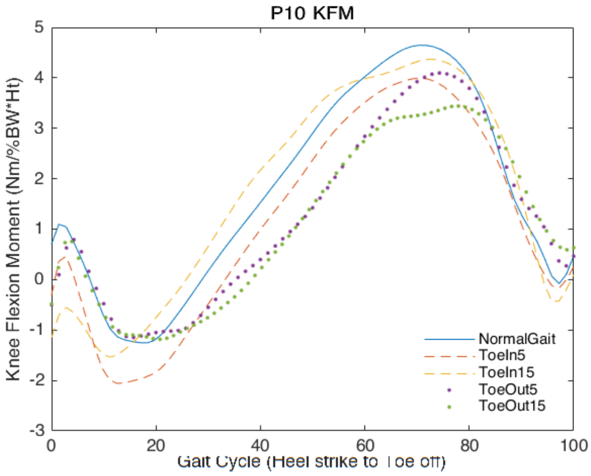


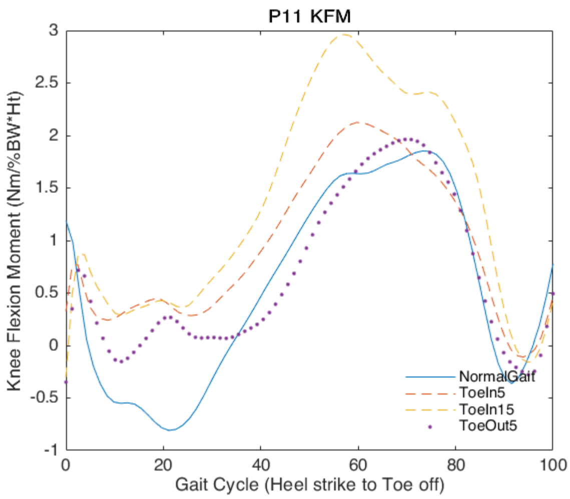


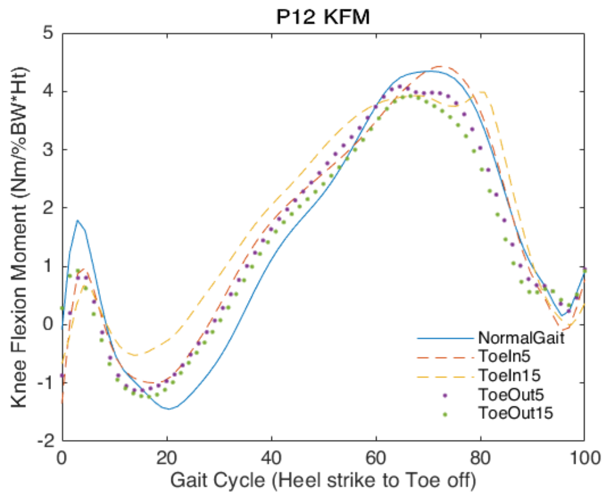


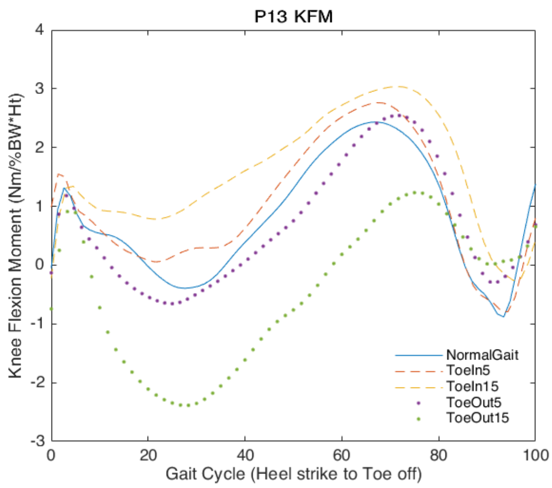


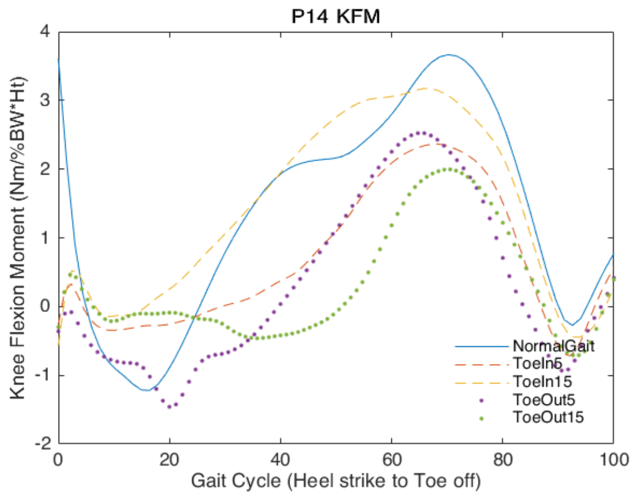


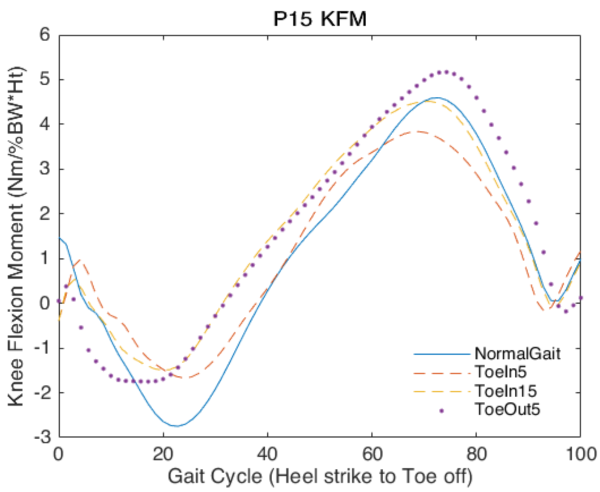


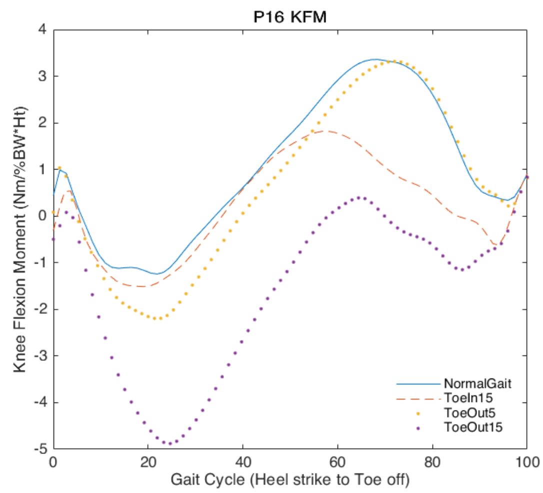

P11 KFM
Knee Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5

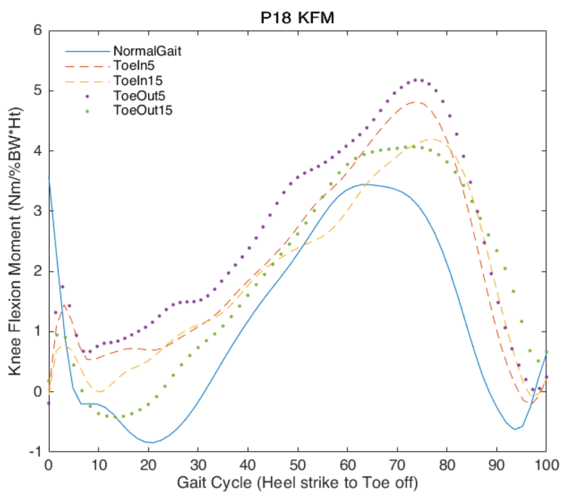

P12 KFM
Knee Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

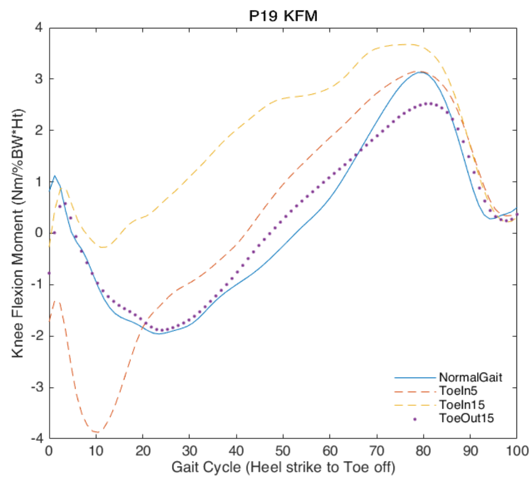

P13 KFM
Knee Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

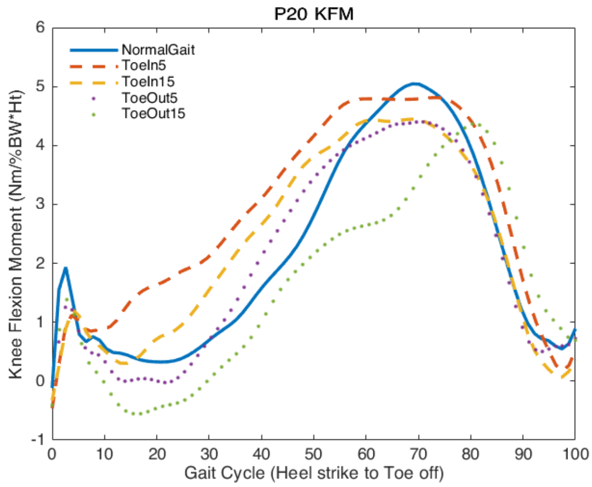

P14 KFM
Knee Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15


P15 KFM
Knee Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5


P16 KFM
Knee Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn15
ToeOut5
ToeOut15


P18 KFM
Knee Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15


P19 KFM
Knee Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut15



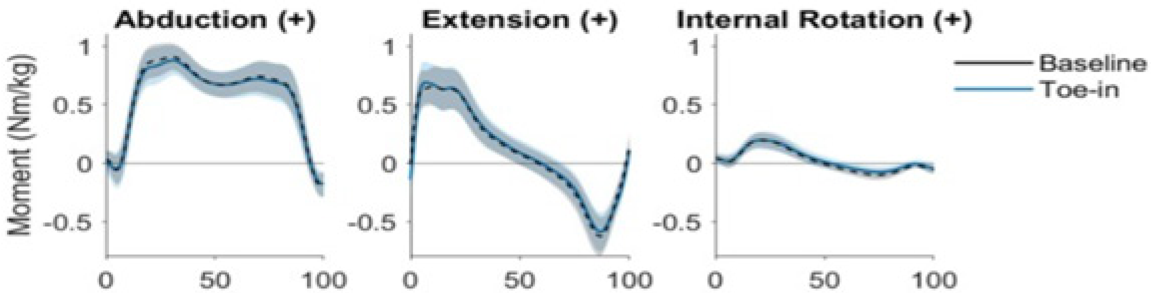
	1st peak KFM				2nd peak KFM			
	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)
P1	-90.1	-23.5	-190.1	-354.3	-12.6	-43.5	-59.7	-59.7
P2	20.1	66.3	4.8	-3.2	11.1	11.1	16.0	-17.3
P7	-7.1	-53.3	-8.0	-16.4	62.3	51.9	48.6	54.1
P8	81.8	-	87.8	31.2	-20.8	-	-24.2	4.4
P9	233.3	-	-80.0	-6.7	-1.6	-	-37.8	-16.3
P10	-64.0	-23.2	8.0	5.6	-14.2	-6.2	-11.8	-26.0
P11	135.8	144.4	81.5	-	14.6	60	5.9	-
P12	31.0	64.1	22.8	15.9	2.1	-10.1	-6.0	-9.7
P13	112.8	300.0	-69.2	-512.8	13.1	24.2	4.1	-19.6
P14	71.9	88.4	15.7	70.3	-35.2	-13.4	-31.1	-45.4
P15	39.3	45.4	36.4	-	-16.3	-1.5	12.6	-
P16	-	- 21.8	-76.6	-293.6	-	-45.8	-1.5	-88.4
P18	164.3	100.0	179.8	50.0	40.1	21.8	50.3	18.3
P19	-98.0	86.2	-	4.6	0.0	16.8	-	-20
P20	164.3	- 9.1	-106.1	-264.3	-4.5	-11.7	12.7	-13.7
Mean ± SD (%)	63.26 ± 97.91	58.76 ± 93.98	-6.66 ± 98.61	-97.98 ± 189.76	2.72 ± 24.23	4.12 ± 28.91	-1.64 ± 29.54	-18.41 ± 36.91
Mean ± SD (Nm/kg)	-1.02 ± 1.26	-0.75 ± 1.04	-1.14 ± 0.98	-1.82 ± 1.35	3.33 ± 0.98	3.50 ± 1.02	3.17 ± 1.17	2.66 ± 1.27

Table: Values for KFM

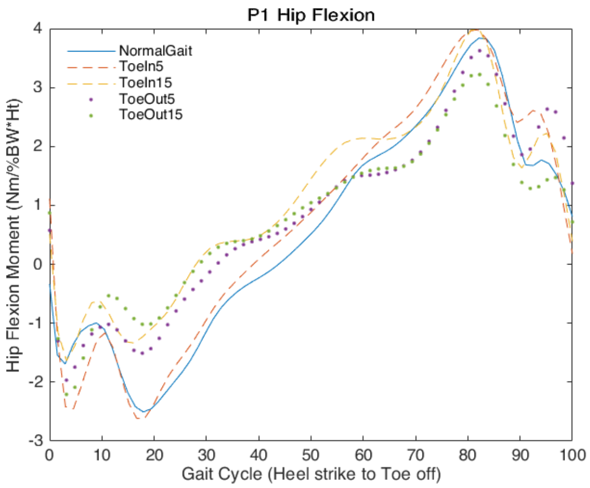
The influence of changing the FPA on the pKFM, all values are compared to the value of the normal gait expressed in percent. The percentages below 5% are marked grey, since a reduction in pKAM of 5% or more is, according to literature (Shimada et al., 2006), associated with improved knee moment and pain. The lowest two rows show the mean value per FPA in percentage, and the mean value per FPA in Nm/kg.

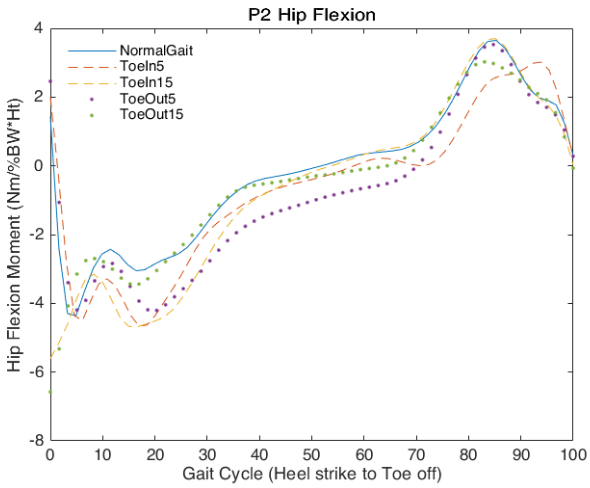
Graphs of hip moments

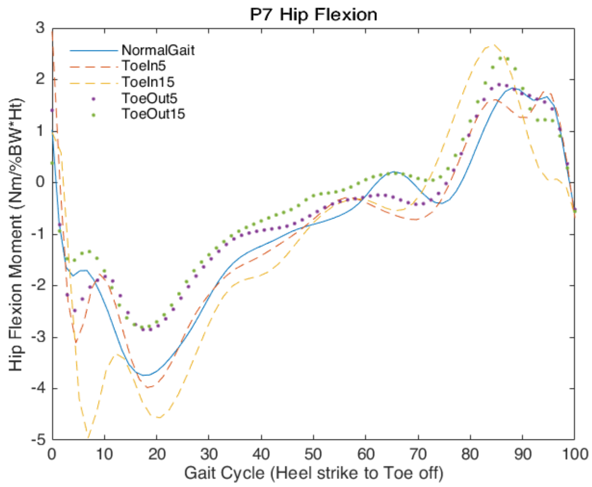
The following graphs of the hip moments are included in the appendix to prove that the values are correct according to literature. In the literature (Seagers et al., 2022a) graphs are shown of the moment of the hip joint relative to the body weight. While in the report the moment is relative to the body weight times the length of the participant. Combining both the weight and the length gives a better result to compare between participants. The first figure below shows the abduction, the extension and the internal rotation. The internal rotation stays the same, but the adduction and flexion are mirrored compared to these graphs. This since the movements in the body are the opposites, flexion – extension and abduction – adduction.

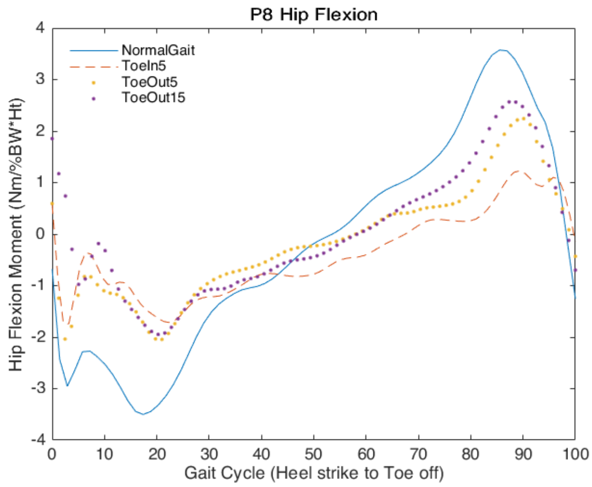


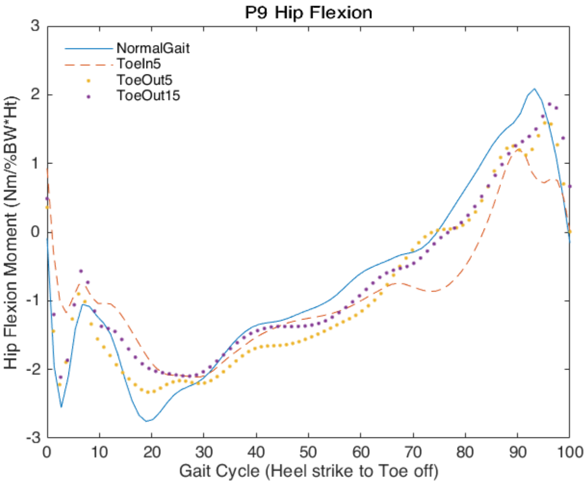
Graphs of hip flexion moment

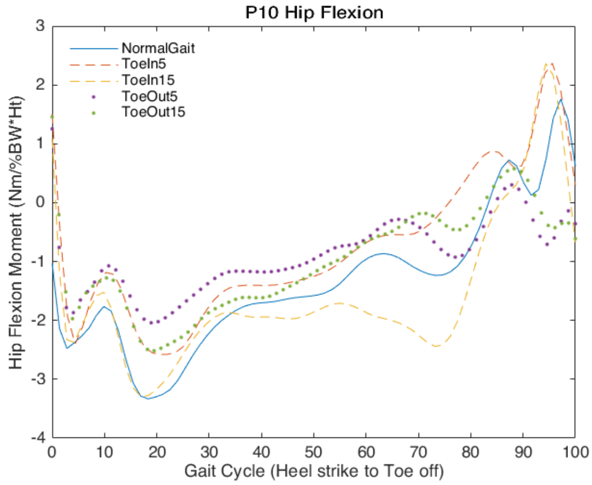


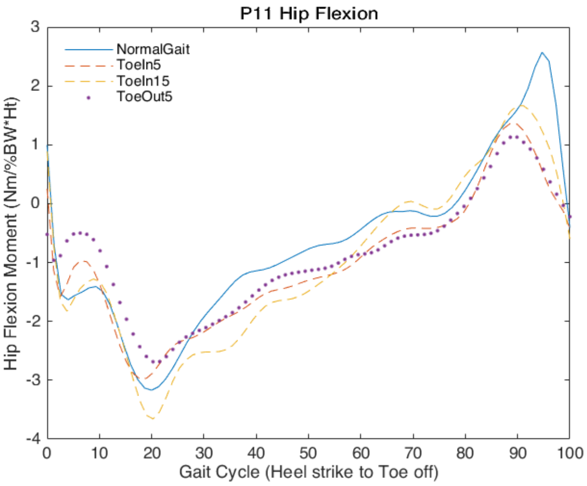


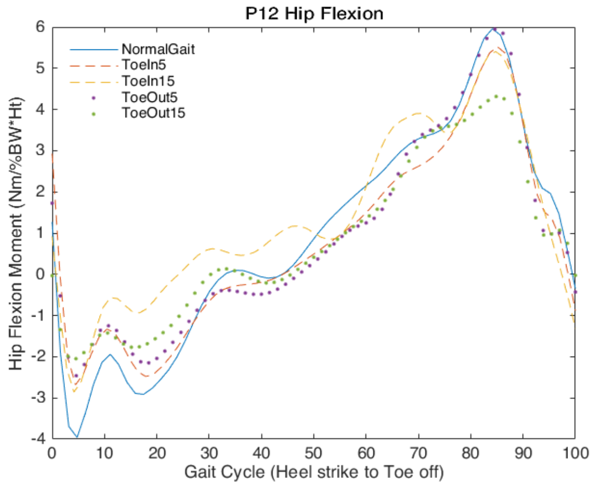


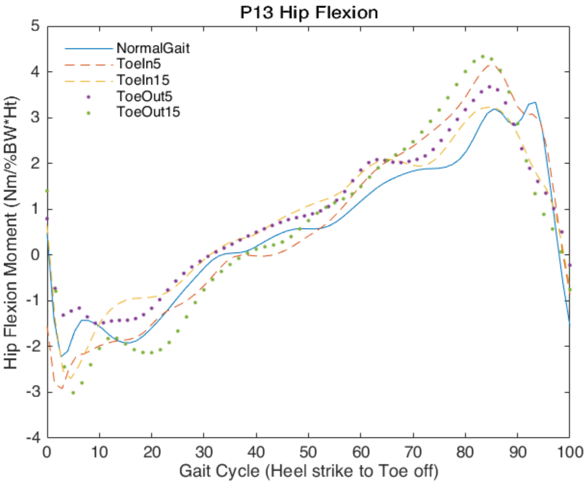


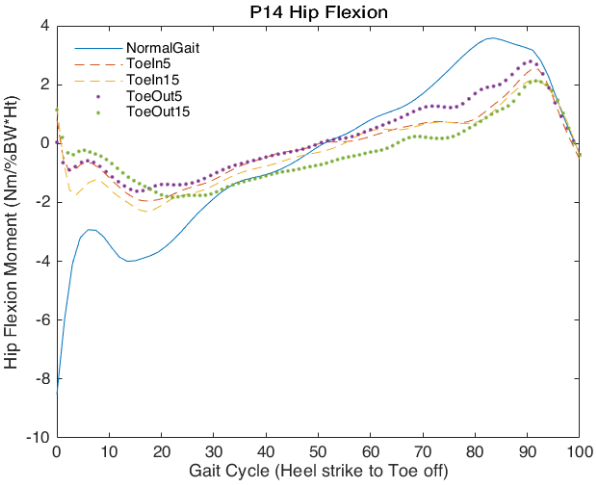

P9 Hip Flexion
NormalGait
ToeIn5
ToeOut5
ToeOut15
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

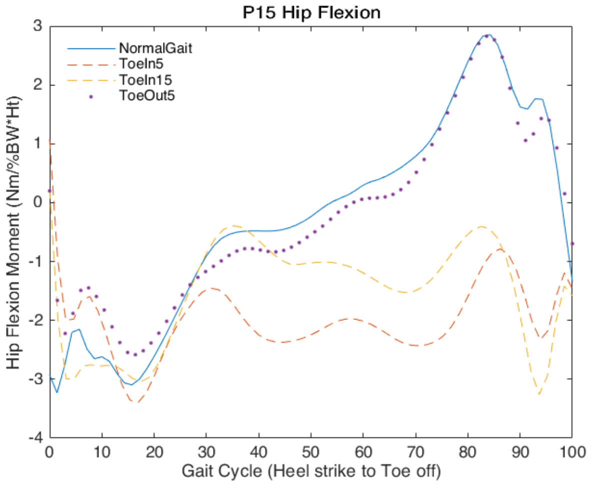

P10 Hip Flexion
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

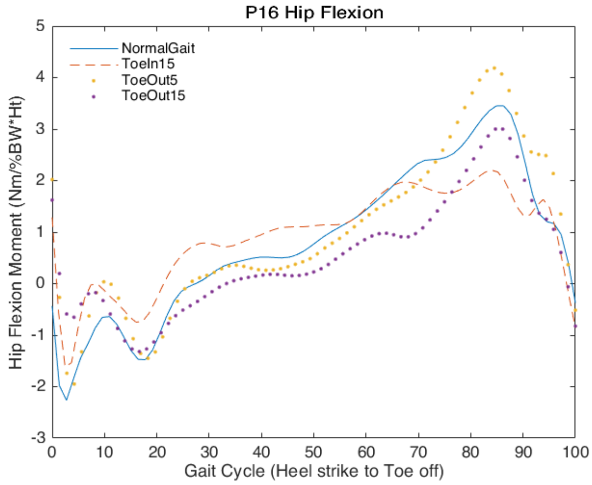

P11 Hip Flexion
NormalGait
ToeIn5
ToeIn15
ToeOut5
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

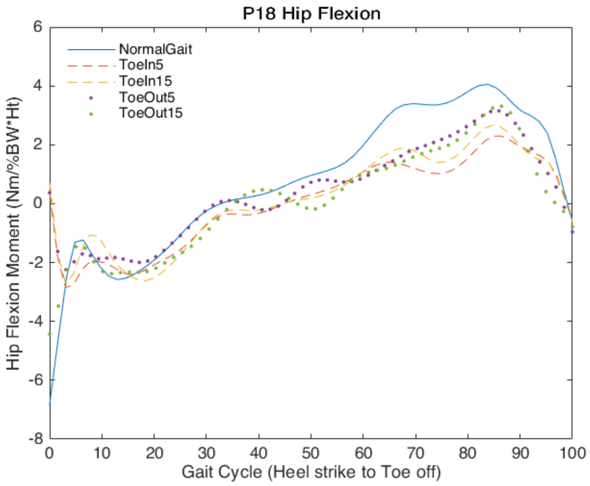

P12 Hip Flexion
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

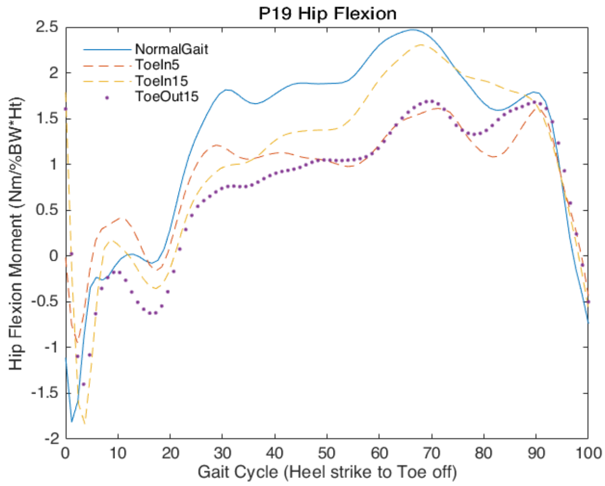

P13 Hip Flexion
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

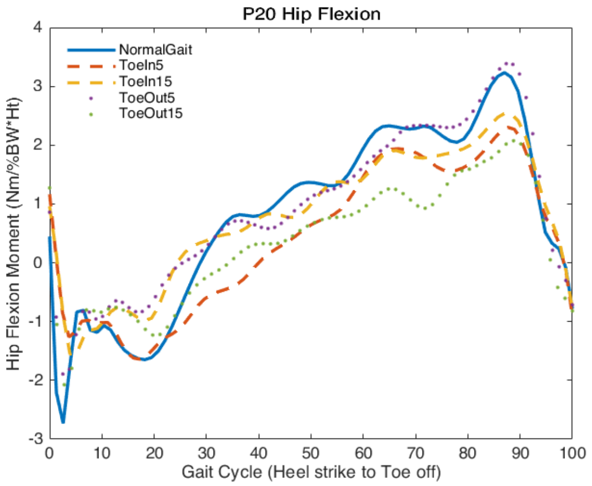

P14 Hip Flexion
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)


P15 Hip Flexion
NormalGait
ToeIn5
ToeIn15
ToeOut5
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)


P16 Hip Flexion
NormalGait
ToeIn15
ToeOut5
ToeOut15
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)


P18 Hip Flexion
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

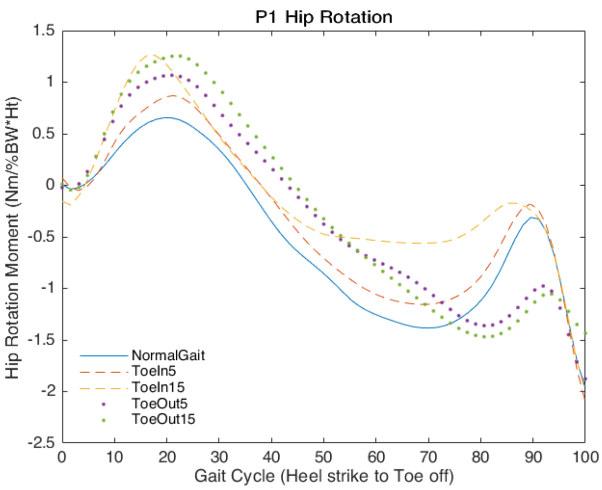

P19 Hip Flexion
NormalGait
ToeIn5
ToeIn15
ToeOut15
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

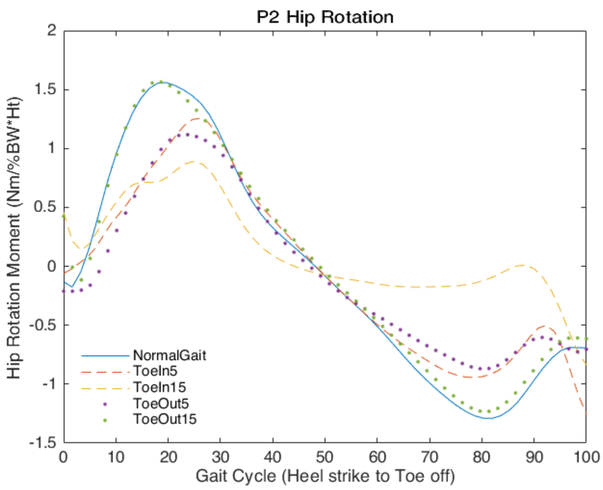

P20 Hip Flexion
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Flexion Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

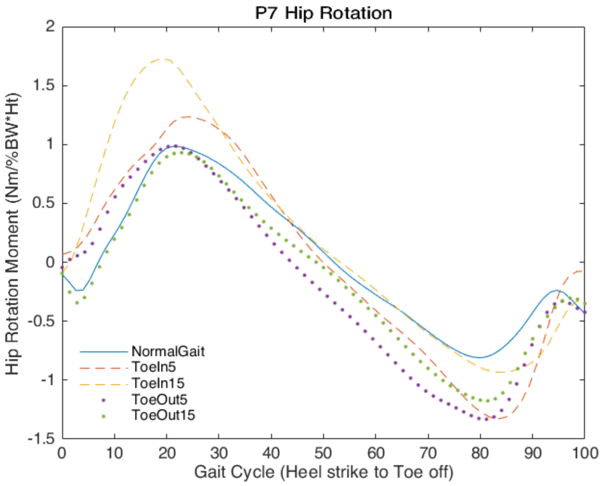
Peak value					Area under curve			
	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)
P1	3.6	3.6	-5.7	-16.1	8.9	-12.5	-17.0	-27.7
P2	-17.3	1.3	-3.3	-17.3	12.6	26.2	19.4	-1.9
P7	-12.5	45.7	3.3	31.0	-5.6	0.9	-19.6	-27.1
P8	-65.5	-	37.3	-28.0	-38.2	-	-39.8	-35.0
P9	-42.6	-	-23.4	-11.0	-23.0	17.7	-37.2	-24.8
P10	34.7	34.1	-83.0	-67.6	-23.0	17.7	-37.2	-24.8
P11	-47.1	-35.4	-56.0	-	1.1	21.3	-4.3	-
P12	-7.4	-9.2	-0.2	-27.5	-12.0	-3.5	-12.7	-25.4
P13	29.5	1.3	15.0	35.7	12.0	-9.3	-12.0	-0.9
P14	-29.5	-39.6	-22.3	-40.7	-43.5	-39.5	-39.5	40.1
P15	-72.3	-86.0	-0.7	-	33.7	-1.0	-15.3	-
P16	-	-36.2	21.2	-13.0	-	-7.0	-2.0	-34.0
P18	-43.5	-34.1	-22.2	-18.3	-32.5	-30.2	-31.0	-32.5
P19	-34.8	-6.5	-	-32.0	-31.5	-18.5	-	-30.6
P20	-28.8	-21.4	5.0	-35.9	-20.5	-21.4	-9.4	-42.7
Mean ± SD (%)	-23.79 ± 30.68	-14.03 ± 30.40	-9.64 ± 29.69	-18.59 ± 26.32	-11.61 ± 21.85	-4.15 ± 19.05	-18.40 ± 16.55	-18.95 ± 20.39

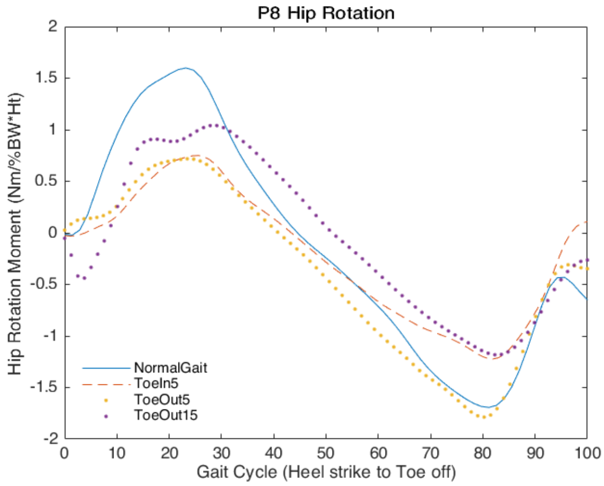
Table: Hip flexion moment values
The increase and decrease for the values in the hip flexion moment, divided into the peak KAM values for each gait modification, and the area under the curve for each gait modification. All values are compared to the value of the normal gait and expressed in percentages

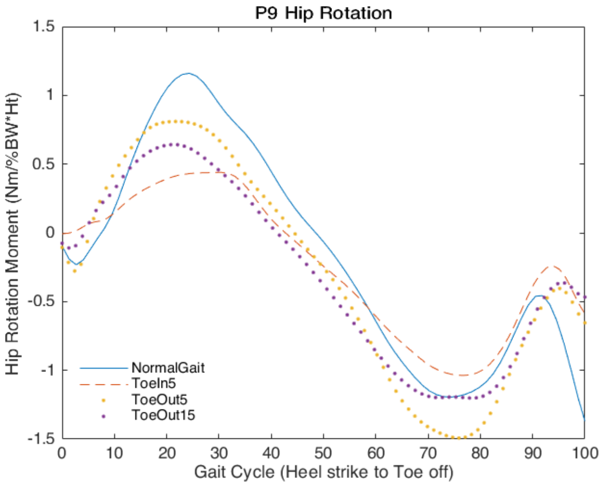
Graphs of hip rotation moment

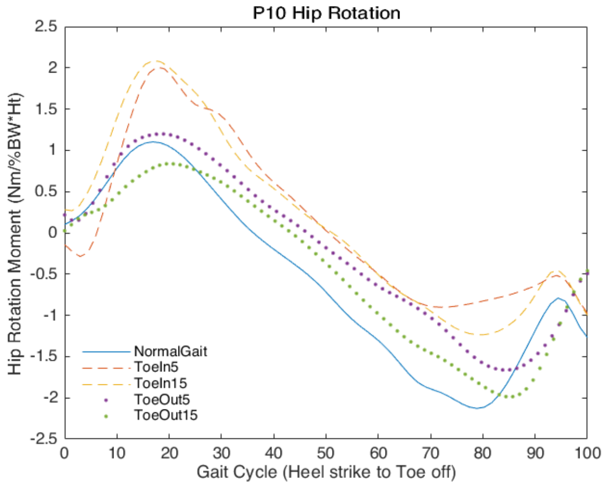


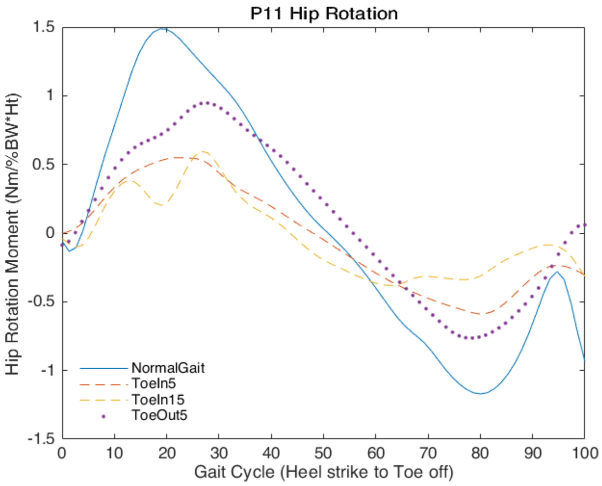


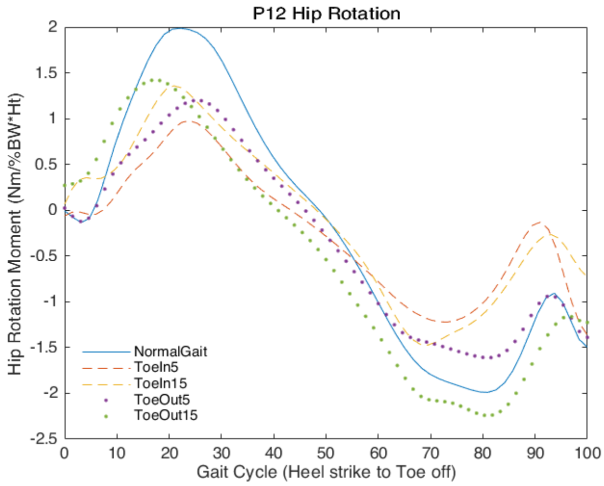

P7 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

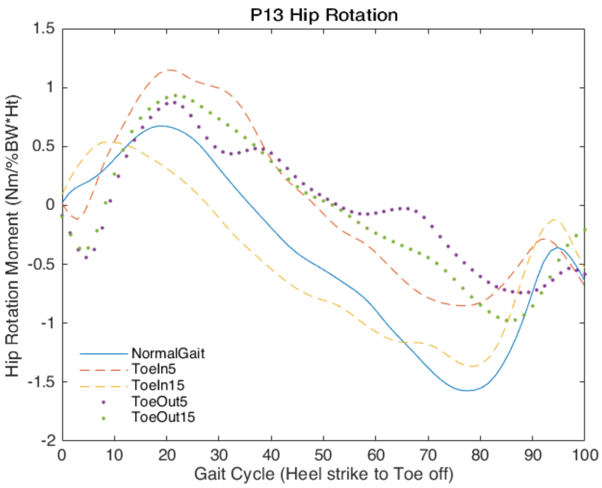

P8 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeOut5
ToeOut15

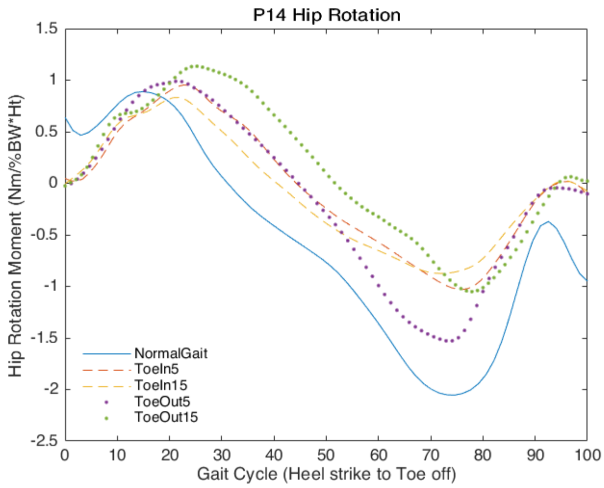

P9 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeOut5
ToeOut15

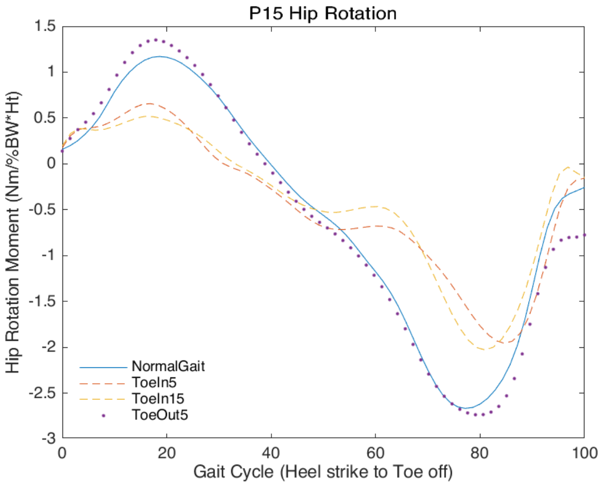

P10 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

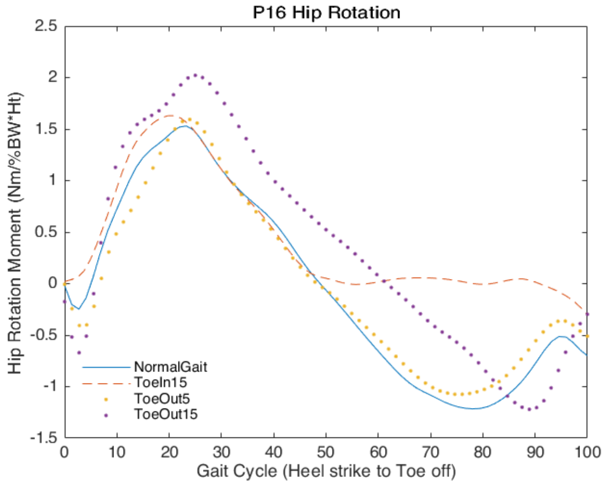

P11 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5

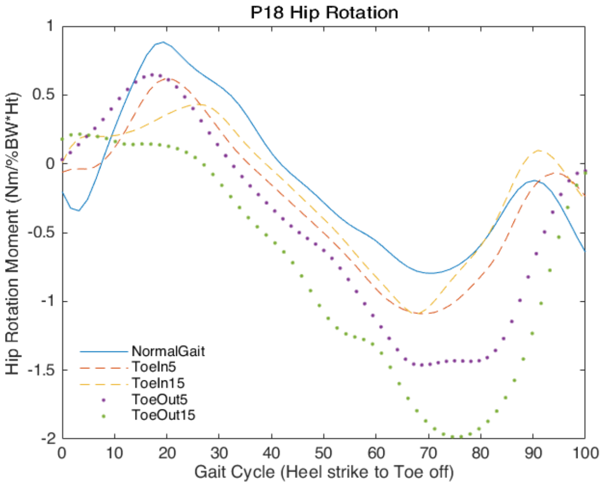

P12 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

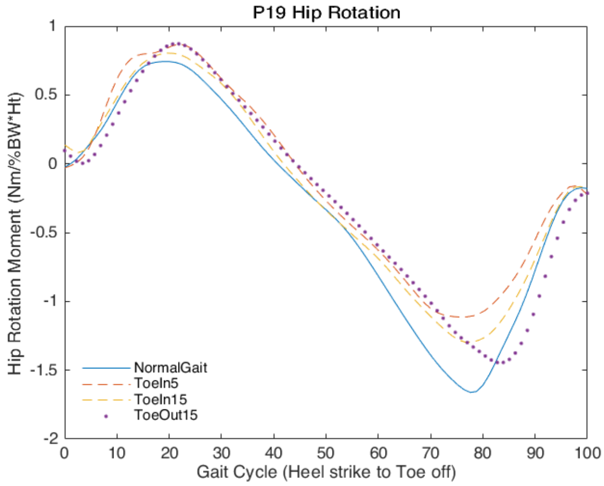

P13 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

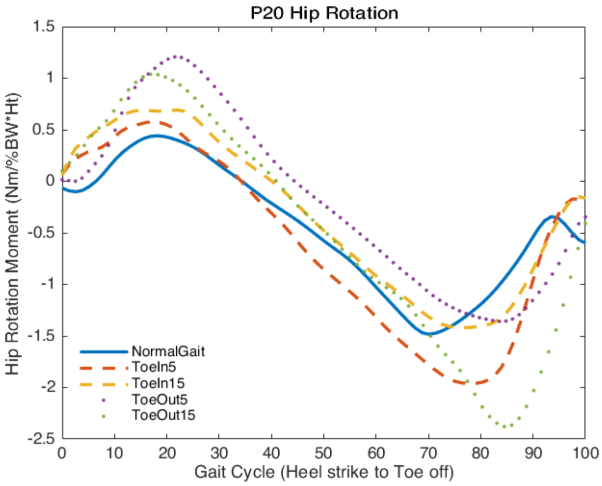

P14 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15


P15 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5


P16 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn15
ToeOut5
ToeOut15


P18 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

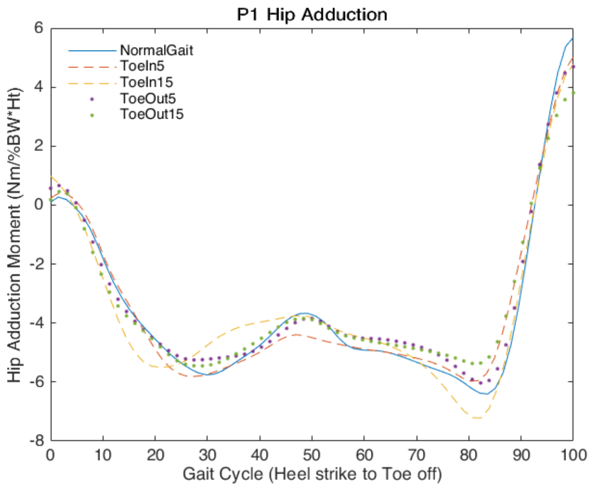

P19 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut15

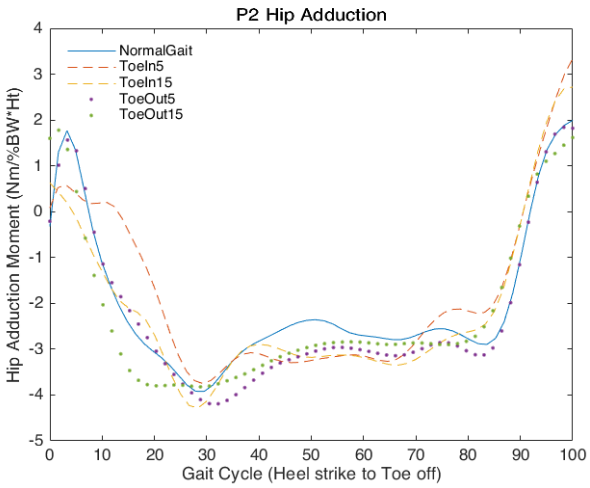

P20 Hip Rotation
Hip Rotation Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

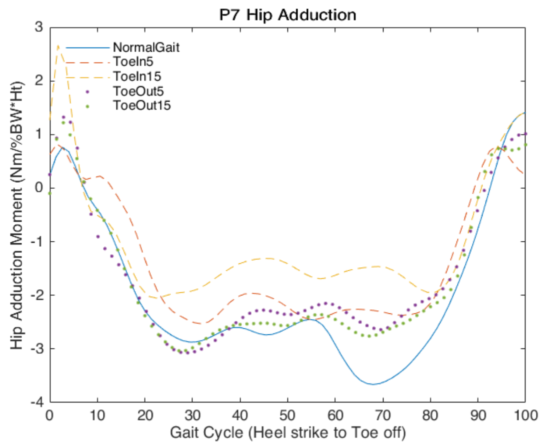
Peak value					Area under curve			
	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)
P1	33.8	93.8	64.6	92.3	-8.2	-30.6	0.0	10.2
P2	-19.2	-42.9	-28.2	0.0	-16.3	-63.3	-30.2	-6.1
P7	25.5	76.5	1.0	-6.1	24.3	16.2	21.6	8.1
P8	-53.1	-	-55.6	-35.0	-17.7	-	-6.5	-16.1
P9	-62.9	-	-30.2	-44.8	-26.0	-	16.0	-8.0
P10	82.7	90.0	9.1	-23.6	-23.6	-9.7	-13.9	-5.6
P11	-63.1	-59.7	-36.2	-	-52.7	-63.6	-29.1	-
P12	-50.8	-31.7	-39.7	-28.6	-52.7	-63.6	-29.1	-
P13	71.6	-19.4	29.9	38.8	-22.6	-37.1	-9.7	-11.3
P14	6.7	-6.7	9.0	27.0	-27.4	-37.1	-9.7	-11.3
P15	-43.6	-55.6	15.4	-	-38.2	-46.1	7.9	-
P16	-	6.5	3.9	32.0	-	-39.0	-15.3	10.2
P18	-30.7	-51.1	-26.1	-84.1	10.7	-3.6	57.1	82.1
P19	16.2	8.1	-	17.6	-10.5	-12.3	-	-3.5
P20	31.8	56.8	175.0	136.4	46.8	12.8	23.4	51.1
Mean ± SD (%)	-1.01 ± 47.56	4.89 ± 54.43	6.56 ± 36.17	9.38 ± 56.53	-13.88 ± 26.57	-29.00 ± 26.54	-1.25 ± 25.15	8.32 ± 28.05

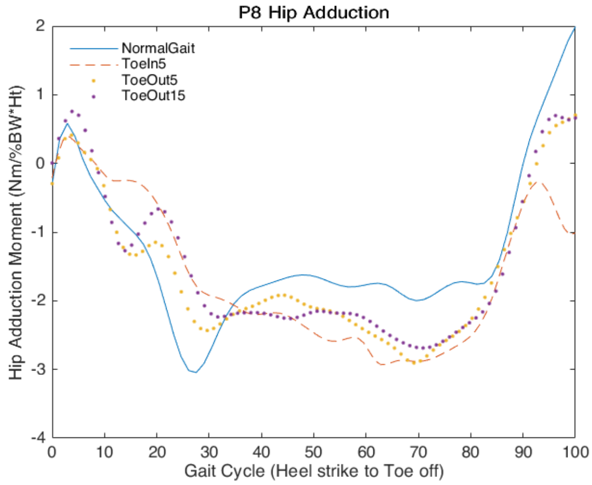
Table: Hip rotation moment values
The influence of changing the FPA on the hip rotation moment, divided into the peak values for each gait modification, and the area under the curve for each gait modification. All values are compared to the value of the normal gait expressed in percentages

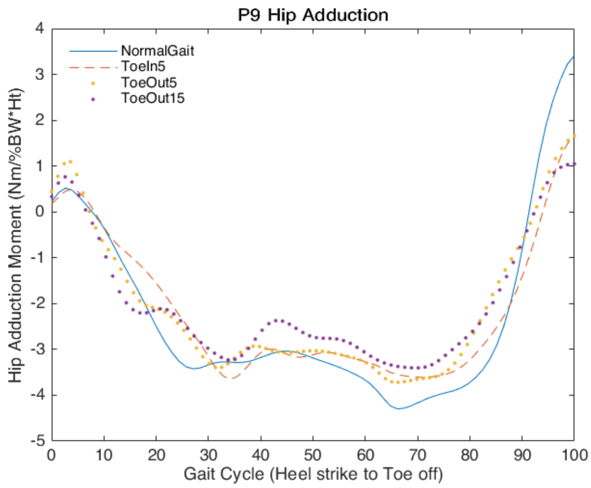
Graphs of hip adduction moment

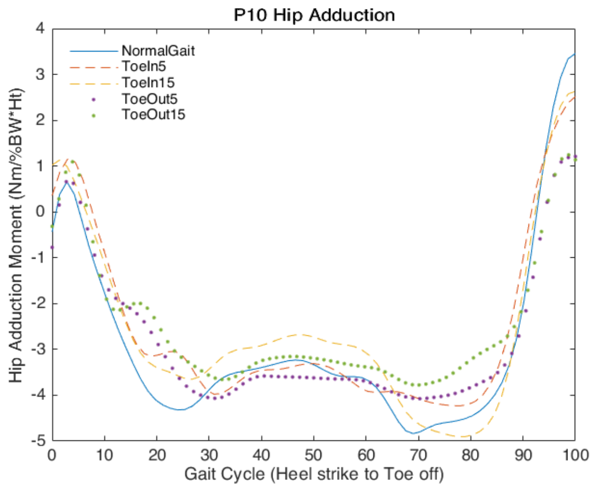


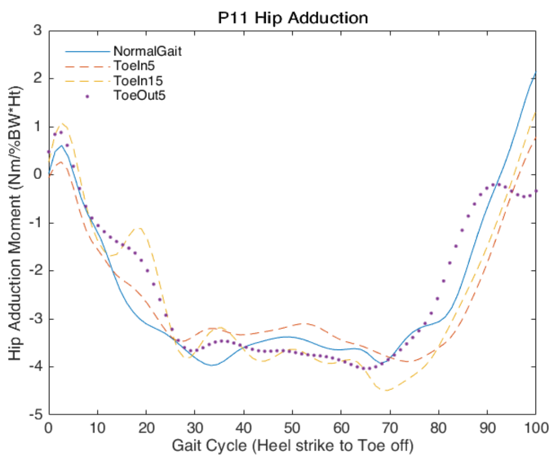


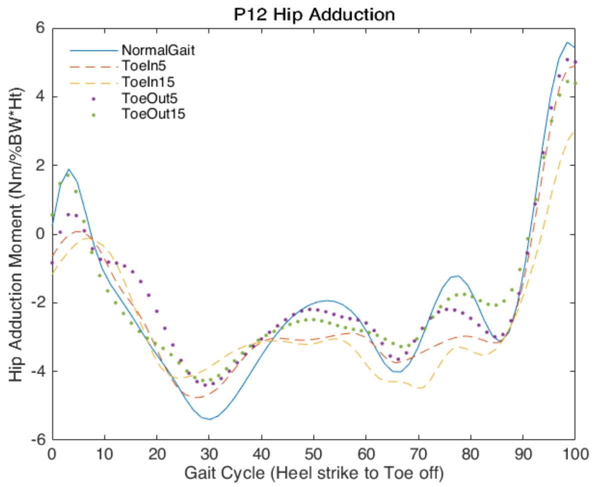

P7 Hip Adduction
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

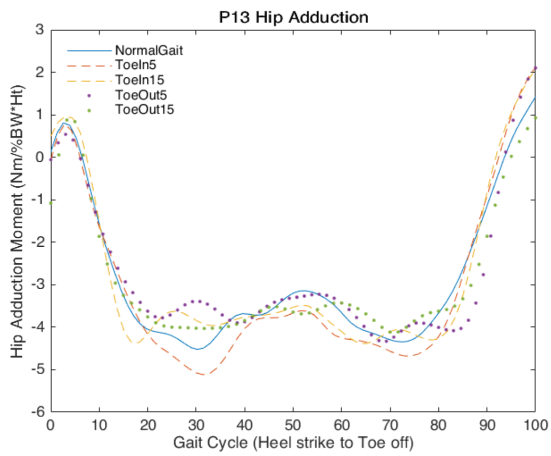

P8 Hip Adduction
NormalGait
ToeIn5
ToeOut5
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

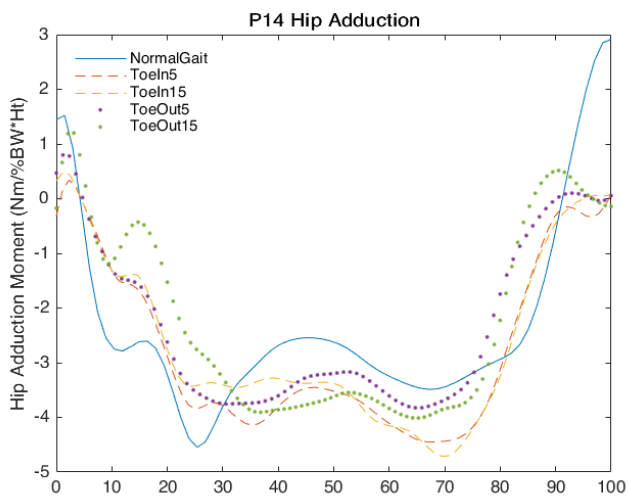

P9 Hip Adduction
NormalGait
ToeIn5
ToeOut5
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

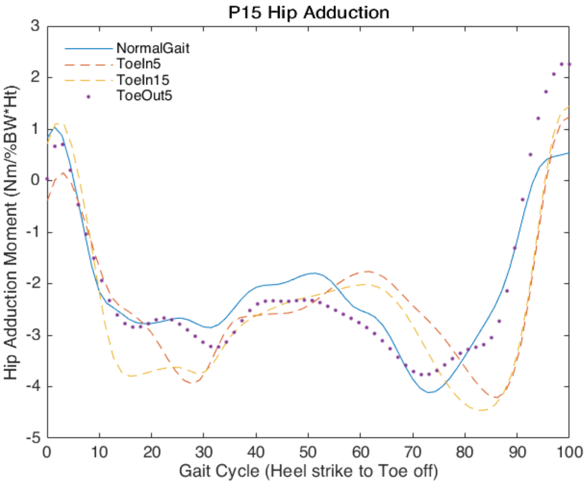

P10 Hip Adduction
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

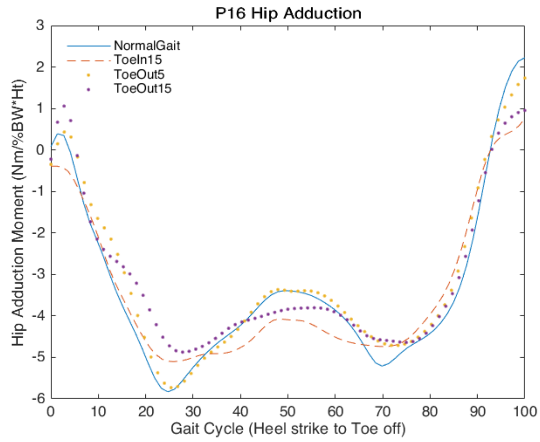

P11 Hip Adduction
NormalGait
ToeIn5
ToeIn15
ToeOut5
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

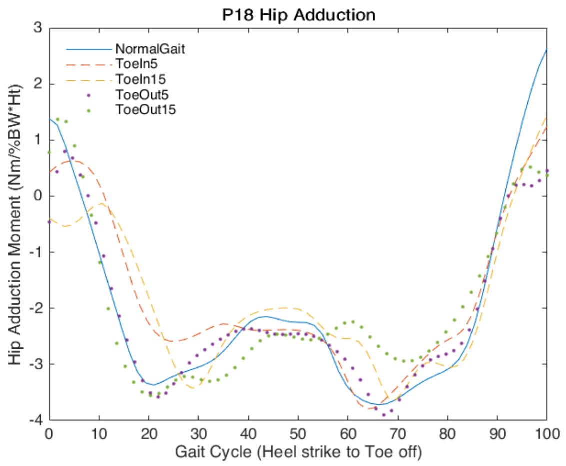

P12 Hip Adduction
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

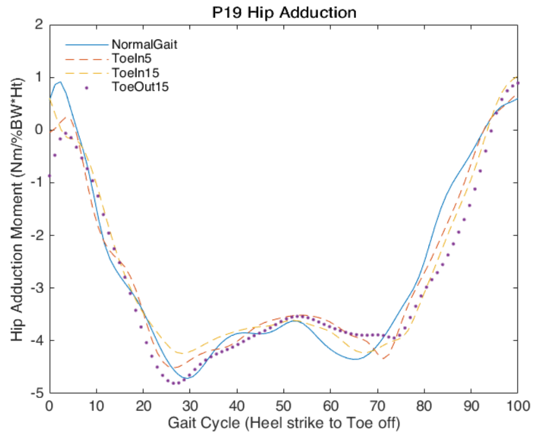

P13 Hip Adduction
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

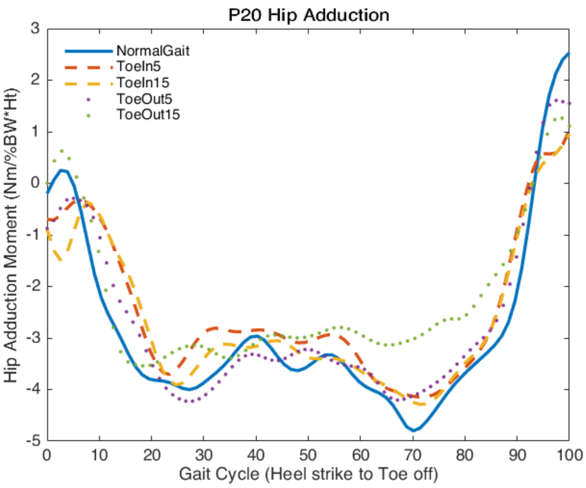

P14 Hip Adduction
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)


P15 Hip Adduction
NormalGait
ToeIn5
ToeIn15
ToeOut5
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)


P16 Hip Adduction
NormalGait
ToeIn15
ToeOut5
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)


P18 Hip Adduction
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

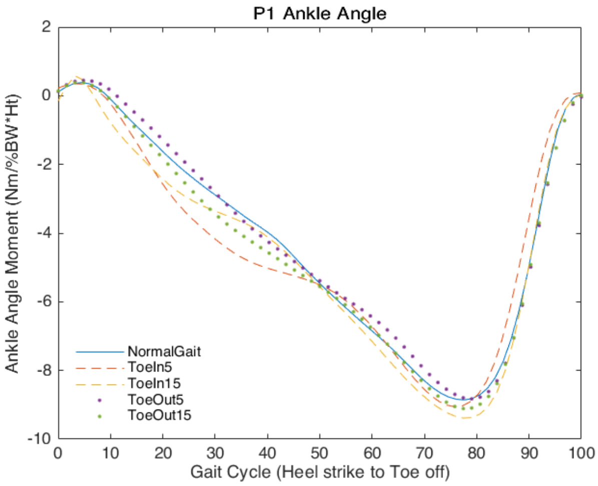

P19 Hip Adduction
NormalGait
ToeIn5
ToeIn15
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

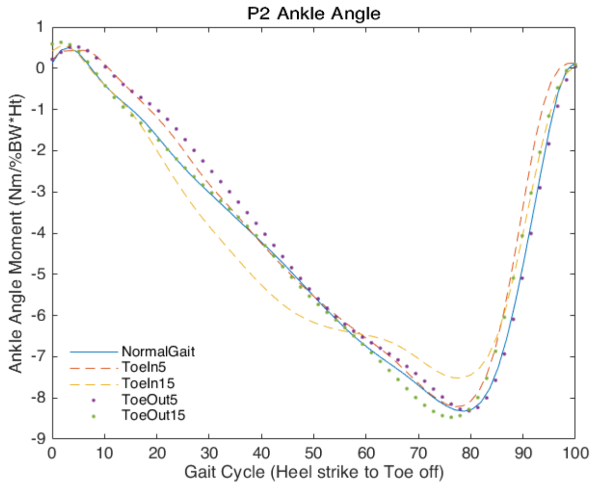

P20 Hip Adduction
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15
Hip Adduction Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)

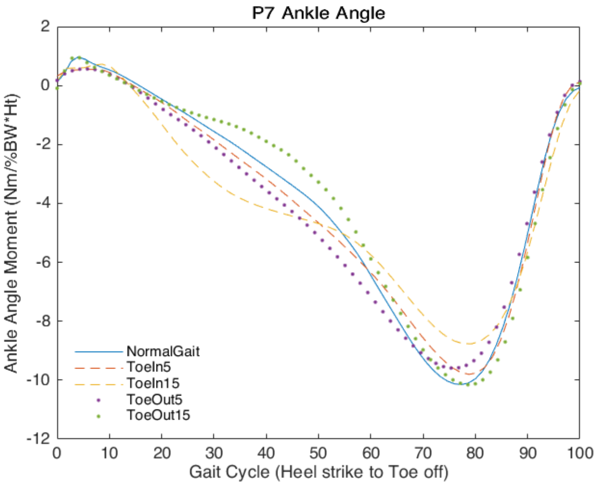
	Peak value				Area under curve			
	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)
P1	7.2	-12.6	5.9	16.4	-2.8	-7.7	-11.3	-14.1
P2	4.3	-9.2	-6.9	2.6	-2.8	-7.7	-11.3	-14.1
P7	35.5	47.0	27.9	24.6	-0.7	4.1	6.8	5.4
P8	27.6	-	20.1	26.6	45.8	-	27.1	22.4
P9	16.0	-	13.7	20.9	-4.0	-	-3.0	-15.8
P10	13.0	-1.2	15.9	21.9	-13.2	-9.8	-5.6	-11.5
P11	13.1	3.8	7.8	-	3.4	6.9	-3.4	-
P12	11.9	22.4	18.5	21.1	7.2	14.1	-9.4	-5.0
P13	-13.3	19.9	24.8	11.1	1.3	-9.1	-14.7	-21.2
P14	15.6	24.6	17.8	14.3	31.5	17.9	9.8	22.3
P15	-2.4	-8.3	8.3	-	0.6	8.2	5.0	-
P16	-	12.7	1.7	16.5	-	8.0	-9.5	-9.1
P18	-1.9	2.7	-4.8	21.0	-9.9	-11.3	-4.0	-11.9
P19	5.1	10.2	-	-1.9	1.2	-4.9	-	6.1
P20	13.7	10.6	12.5	34.8	-13.0	-12.6	-4.2	-27.2
Mean ± SD (%)	10.39 ± 11.87	9.43 ± 15.88	11.66 ± 9.97	17.68 ± 9.40	3.10 ± 15.79	-0.38 ± 10.07	-1.98 ± 10.62	-5.67 ± 14.85

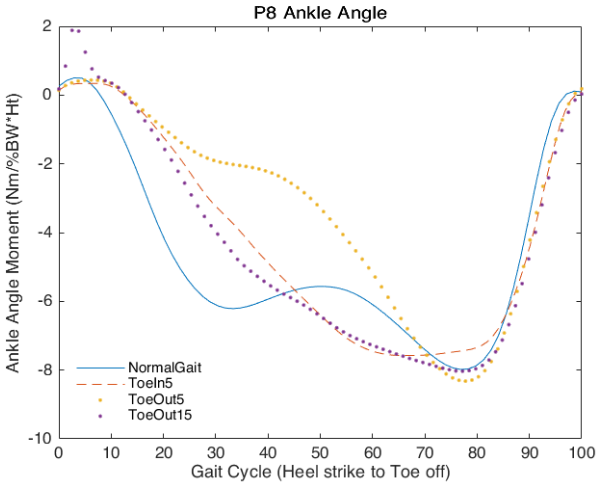
Table: Hip adduction moment values
The influence of changing the FPA on the hip adduction moment, divided into the peak values for each gait modification, and the area under the curve for each gait modification. All values are compared to the value of the normal gait expressed in percentages

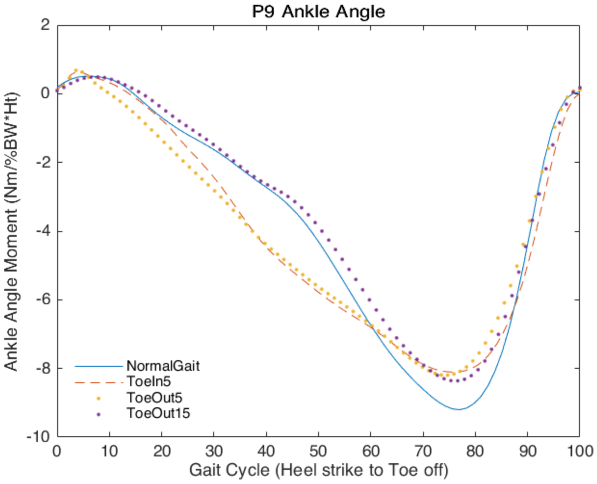
Graphs of ankle angle moment

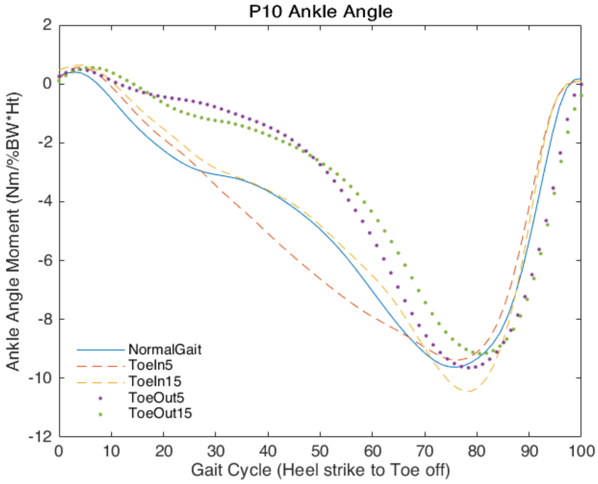


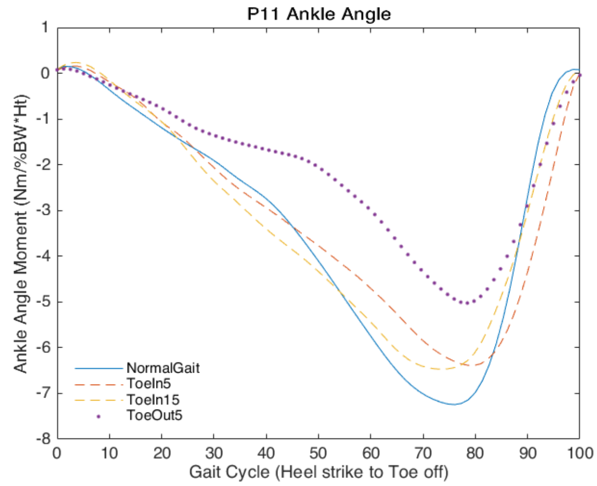


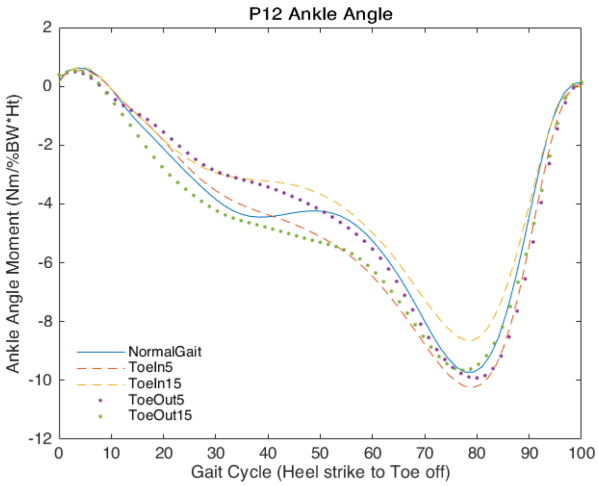

P7 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

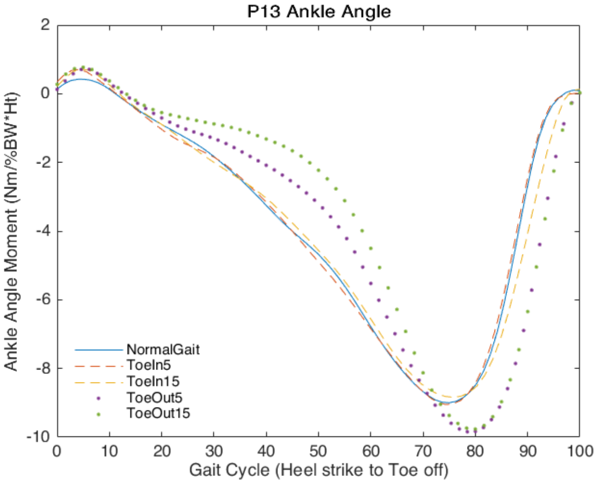

P8 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeOut5
ToeOut15

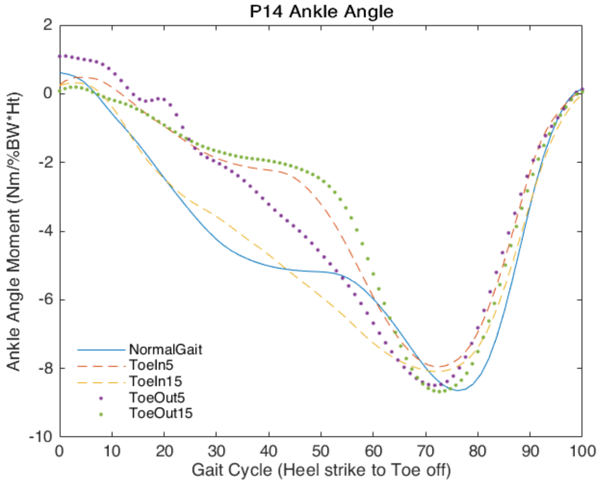

P9 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeOut5
ToeOut15

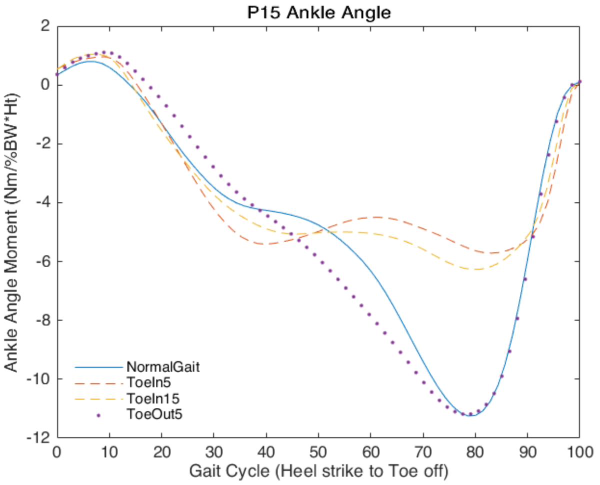

P10 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

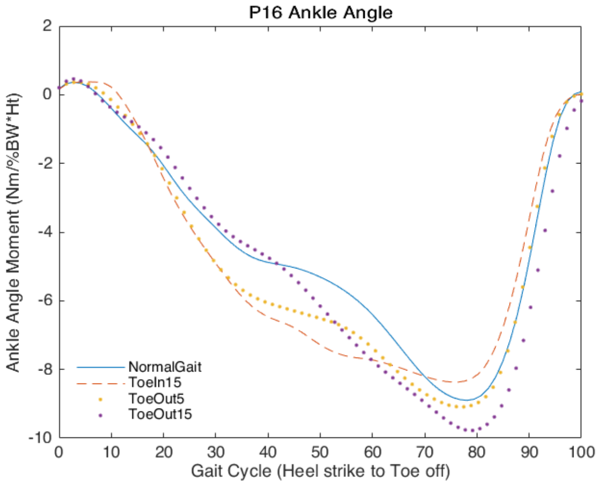

P11 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5

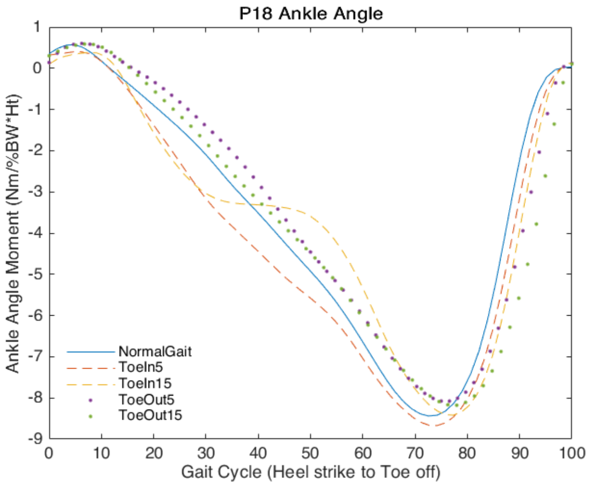

P12 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

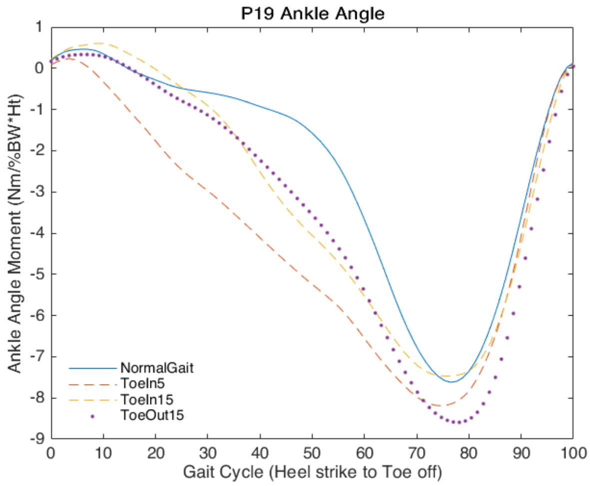

P13 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

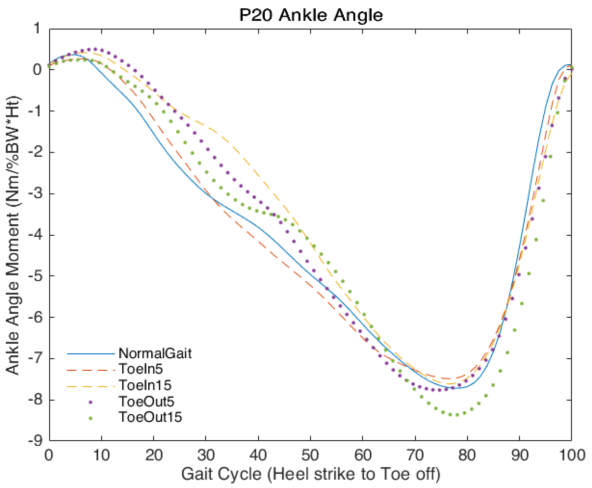

P14 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15


P15 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5


P16 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn15
ToeOut5
ToeOut15


P18 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15


P19 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut15


P20 Ankle Angle
Ankle Angle Moment (Nm/%BW*Ht)
Gait Cycle (Heel strike to Toe off)
NormalGait
ToeIn5
ToeIn15
ToeOut5
ToeOut15

	Peak value				Area under curve			
	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)	Toe-in 5 (%)	Toe-in 15 (%)	Toe-out 5 (%)	Toe-out 15 (%)
P1	-2.1	-5.8	0.3	-2.8	3.5	-0.3	-8.7	-3.1
P2	1.6	9.7	0.5	-1.8	-0.4	-0.8	-7.3	-3.9
P7	3.4	13.7	5.5	0.0	-11.2	-19.1	-4.0	-11.2
P8	5.4	-	-4.3	-0.6	22.9	-	15.6	11.6
P9	11.8	-	11.0	9.1	19.6	-	189.0	-4.9
P10	2.5	-8.5	-0.2	4.7	0.6	-3.4	-16.8	-15.8
P11	11.7	10.6	30.7	-	1.6	4.5	-31.0	-
P12	-5.3	11.1	-2.1	0.6	15.7	-0.4	2.6	-28.2
P13	-0.6	1.8	-9.3	-8.4	-7.7	-11.1	-13.9	-28.2
P14	8.2	6.5	1.8	-0.2	-3.5	22.8	4.5	2.1
P15	49.1	44.2	-0.5	-	-26.3	-27.2	1.5	-
P16	-	6.0	-2.1	-9.9	-	21.7	8.0	9.8
P18	-2.7	0.2	4.3	2.1	20.6	7.0	-0.9	-1.3
P19	-7.5	2.1	-	-12.7	66.4	23.8	-	41.1
P20	6.1	13.7	3.2	2.5	19.6	6.6	9.8	-13.0
Mean ± SD (%)	5.83 ± 13.27	8.10 ± 12.38	2.76 ± 8.99	-1.34 ± 5.78	8.67 ± 21.07	1.85 ± 14.83	10.60 ± 50.80	-3.46 ± 17.55

Table: Ankle angle moment values
The influence of changing the FPA on the ankle angle moment, divided into the peak values for each gait modification, and the area under the curve for each gait modification. All values are compared to the value of the normal gait expressed in percent

Appendix D: Statistical tests

Tables post-hoc tests KAM and KFM

Table post-hoc tests KAM

Pairwise Comparisons

Measure: gait

(I) peak	(J) peak	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	,264	,126	,699	-,220	,749
	3	,620*	,143	,025	,071	1,169
	4	,129	,116	1,000	-,314	,572
	5	,090	,145	1,000	-,468	,648
2	1	-,264	,126	,699	-,749	,220
	3	,356	,135	,302	-,163	,874
	4	-,136	,164	1,000	-,762	,491
	5	-,174	,137	1,000	-,700	,351
3	1	-,620*	,143	,025	-1,169	-,071
	2	-,356	,135	,302	-,874	,163
	4	-,491	,186	,298	-1,204	,222
	5	-,530	,198	,279	-1,288	,228
4	1	-,129	,116	1,000	-,572	,314
	2	,136	,164	1,000	-,491	,762
	3	,491	,186	,298	-,222	1,204
	5	-,039	,087	1,000	-,373	,295
5	1	-,090	,145	1,000	-,648	,468
	2	,174	,137	1,000	-,351	,700
	3	,530	,198	,279	-,228	1,288
	4	,039	,087	1,000	-,295	,373

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Table post-hoc tests KFM

Pairwise Comparisons

Measure: gait

(I) peak	(J) peak	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
1	2	,264	,458	1,000	-1,484	2,013
	3	,382	,451	,996	-1,338	2,102
	4	-,518	,686	,998	-3,135	2,099
	5	,600	,316	,626	-,604	1,804
2	1	-,264	,458	1,000	-2,013	1,484
	3	,118	,177	,999	-,559	,794
	4	-,782	,976	,997	-4,505	2,941
	5	,336	,397	,996	-1,180	1,851
3	1	-,382	,451	,996	-2,102	1,338
	2	-,118	,177	,999	-,794	,559
	4	-,900	,997	,993	-4,705	2,905
	5	,218	,439	1,000	-1,457	1,893
4	1	,518	,686	,998	-2,099	3,135
	2	,782	,976	,997	-2,941	4,505
	3	,900	,997	,993	-2,905	4,705
	5	1,118	,614	,675	-1,227	3,462
5	1	-,600	,316	,626	-1,804	,604
	2	-,336	,397	,996	-1,851	1,180
	3	-,218	,439	1,000	-1,893	1,457
	4	-1,118	,614	,675	-3,462	1,227

Based on estimated marginal means

a. Adjustment for multiple comparisons: Sidak.

Tables post-hoc tests gait parameters

Table post-hoc tests Gait Speed

Pairwise Comparisons

Measure: MEASURE_1

(I) gait_type	(J) gait_type	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
1	2	,122	,067	,669	-,133	,377
	3	,102	,087	,960	-,231	,436
	4	,069	,065	,978	-,177	,315
	5	,087	,073	,956	-,191	,364
2	1	-,122	,067	,669	-,377	,133
	3	-,020	,033	1,000	-,145	,105
	4	-,053	,036	,854	-,190	,083
	5	-,036	,030	,957	-,150	,079
3	1	-,102	,087	,960	-,436	,231
	2	,020	,033	1,000	-,105	,145
	4	-,033	,056	1,000	-,248	,181
	5	-,016	,042	1,000	-,175	,144
4	1	-,069	,065	,978	-,315	,177
	2	,053	,036	,854	-,083	,190
	3	,033	,056	1,000	-,181	,248
	5	,018	,052	1,000	-,180	,216
5	1	-,087	,073	,956	-,364	,191
	2	,036	,030	,957	-,079	,150
	3	,016	,042	1,000	-,144	,175
	4	-,018	,052	1,000	-,216	,180

Based on estimated marginal means

a. Adjustment for multiple comparisons: Sidak.

Tables post-hoc tests Step Width

Pairwise Comparisons

Measure: MEASURE_1

(I) gait_type	(J) gait_type	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-,679	,171	,072	-1,415	,058
	3	-1,164*	,257	,039	-2,267	-,061
	4	-,201	,114	,742	-,690	,287
	5	-,144	,146	,989	-,771	,483
2	1	,679	,171	,072	-,058	1,415
	3	-,486	,144	,140	-1,104	,132
	4	,477	,196	,405	-,364	1,318
	5	,534	,182	,231	-,246	1,315
3	1	1,164*	,257	,039	,061	2,267
	2	,486	,144	,140	-,132	1,104
	4	,963	,284	,138	-,258	2,184
	5	1,020	,283	,108	-,196	2,236
4	1	,201	,114	,742	-,287	,690
	2	-,477	,196	,405	-1,318	,364
	3	-,963	,284	,138	-2,184	,258
	5	,057	,069	,997	-,240	,355
5	1	,144	,146	,989	-,483	,771
	2	-,534	,182	,231	-1,315	,246
	3	-1,020	,283	,108	-2,236	,196
	4	-,057	,069	,997	-,355	,240

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Sidak.

Tables post-hoc tests Stride Length

Pairwise Comparisons

Measure: MEASURE_1

(I) gait_type	(J) gait_type	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
1	2	,088	,036	,332	-,049	,224
	3	,117	,042	,225	-,045	,279
	4	,136	,077	,711	-,159	,430
	5	,112	,040	,203	-,040	,264
2	1	-,088	,036	,332	-,224	,049
	3	,029	,023	,942	-,060	,117
	4	,048	,066	,999	-,205	,301
	5	,024	,026	,991	-,075	,124
3	1	-,117	,042	,225	-,279	,045
	2	-,029	,023	,942	-,117	,060
	4	,019	,077	1,000	-,275	,313
	5	-,004	,036	1,000	-,142	,133
4	1	-,136	,077	,711	-,430	,159
	2	-,048	,066	,999	-,301	,205
	3	-,019	,077	1,000	-,313	,275
	5	-,023	,078	1,000	-,321	,274
5	1	-,112	,040	,203	-,264	,040
	2	-,024	,026	,991	-,124	,075
	3	,004	,036	1,000	-,133	,142
	4	,023	,078	1,000	-,274	,321

Based on estimated marginal means

a. Adjustment for multiple comparisons: Sidak.

Tables post-hoc tests Trunk Lean

Pairwise Comparisons

Measure: MEASURE_1

(I) gait_type	(J) gait_type	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-3,532*	,606	,004	-5,843	-1,221
	3	-3,609*	,805	,020	-6,680	-,538
	4	-3,598*	,659	,006	-6,114	-1,082
	5	-3,627*	,644	,005	-6,086	-1,167
2	1	3,532*	,606	,004	1,221	5,843
	3	-,077	,588	1,000	-2,321	2,168
	4	-,066	,273	1,000	-1,106	,974
	5	-,094	,727	1,000	-2,868	2,679
3	1	3,609*	,805	,020	,538	6,680
	2	,077	,588	1,000	-2,168	2,321
	4	,011	,542	1,000	-2,056	2,078
	5	-,018	,959	1,000	-3,678	3,642
4	1	3,598*	,659	,006	1,082	6,114
	2	,066	,273	1,000	-,974	1,106
	3	-,011	,542	1,000	-2,078	2,056
	5	-,029	,875	1,000	-3,369	3,311
5	1	3,627*	,644	,005	1,167	6,086
	2	,094	,727	1,000	-2,679	2,868
	3	,018	,959	1,000	-3,642	3,678
	4	,029	,875	1,000	-3,311	3,369

Based on estimated marginal means

*. The mean difference is significant at the ,05 level.

b. Adjustment for multiple comparisons: Sidak.

Tables post-hoc tests Medial Thrust

Pairwise Comparisons

Measure: MEASURE_1

(I) gait_type	(J) gait_type	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	4,213	4,596	,992	-13,326	21,753
	3	-4,306	6,551	,999	-29,307	20,696
	4	4,049	8,005	1,000	-26,502	34,600
	5	-5,184	6,714	,998	-30,809	20,440
2	1	-4,213	4,596	,992	-21,753	13,326
	3	-8,519	4,634	,664	-26,203	9,165
	4	-,164	5,879	1,000	-22,601	22,272
	5	-9,398	4,657	,557	-27,170	8,374
3	1	4,306	6,551	,999	-20,696	29,307
	2	8,519	4,634	,664	-9,165	26,203
	4	8,354	3,902	,487	-6,535	23,244
	5	-,879	7,295	1,000	-28,718	26,961
4	1	-4,049	8,005	1,000	-34,600	26,502
	2	,164	5,879	1,000	-22,272	22,601
	3	-8,354	3,902	,487	-23,244	6,535
	5	-9,233	6,310	,865	-33,314	14,847
5	1	5,184	6,714	,998	-20,440	30,809
	2	9,398	4,657	,557	-8,374	27,170
	3	,879	7,295	1,000	-26,961	28,718
	4	9,233	6,310	,865	-14,847	33,314

Based on estimated marginal means

a. Adjustment for multiple comparisons: Sidak.

Appendix E: Codes

The first 13 Matlab codes need to be placed in the same map, and are used together to convert a matlab file to a .trc and .mot file to import in OpenSim.

RunPreprocessing_file.m

```
clc; close all; clear;
set(0,'DefaultLineLineWidth',2)
%% Run file to convert .mat to .trc and .mot file for OpenSim model
addpath('...')
addpath('...')
%change the location of the second line, this is where the files are saved

clearvars
%% ============ Normal gait trial ========================
load("filename.mat"); matfile = filename; 1
trcfile = "filename.trc";
motfile = "filename.mot";


tInfo.FP = {1, 2, 3}; %{1, 2} to read FP A and B, {1, 2, 3) to read FP A, B and
E
tInfo.limb = {'None', 'R', 'L'}; % {'L', 'R'} to read FP A and B, {'None', 'L',
'R'} to read FP B and E
% hieronder de waardes aangepast voor lengte opname
tInfo.Tstart = 0.00;
tInfo.Tend = 3.00;
stepDect = 0; % for 1, it will detect heelstrikes

err = convertMATtoTRCandMOT(matfile, trcfile, motfile, tInfo, stepDect);
```

Convert_FPtoLabCS.m

```
function GRFTz_lab = convert_FPtoLabCS(GRFTz_FP, fpInfo)
% Purpose:  Converts Fx, Fy, Fz, Tz, COPx, and COPy from the
%           FP coordinate systems to the lab coordinate system
%           for each FP that was hit.

% Get number of analog frames in ‘simulateable’ segment.
nAnalogFrames = length(GRFTz_FP(1).Force);

% For each forceplate of interest ...
nHits = length(GRFTz_FP)
for fpHitNum = 1:nHits

    % Perform rotation transformations to convert Fx, Fy, Fz, and Tz
    % from the FP CS to the lab CS.
    % NOTE:  X_Lab = X_FP,  Y_Lab = -Y_FP,  Z_Lab = -Z_FP
    GRFTz_lab(fpHitNum).Force(1,:) =  GRFTz_FP(fpHitNum).Force(1,:);
    GRFTz_lab(fpHitNum).Force(2,:) = -1 * GRFTz_FP(fpHitNum).Force(2,:);
    GRFTz_lab(fpHitNum).Force(3,:) = -1 * GRFTz_FP(fpHitNum).Force(3,:);
    GRFTz_lab(fpHitNum).Moment(3,:) = -1 *  GRFTz_FP(fpHitNum).Moment(3,:);

    % Initialize arrays for COPx and COPy.
    GRFTz_lab(fpHitNum).COP(1,:) = GRFTz_FP(fpHitNum).COP(1,:);
    GRFTz_lab(fpHitNum).COP(2,:) = GRFTz_FP(fpHitNum).COP(2,:);
    GRFTz_lab(fpHitNum).COP(3,:) = GRFTz_FP(fpHitNum).COP(3,:);
end
return;
```

ConvertMATtoTRC.m

```
function err = convertMATtoTRC(matfile, trcfile, motfile, tInfo)
% Convert c3d data file to .trc and .mot for OpenSim
% USAGE: error = convertC3DtoTRCandMOT(c3dfile, trcfile, motfile)

%%==================== get Markerdata from Matfile =================

%%% put markers in correct format for writeMarkersToTRC
Markers = [];
for ii = 1:matfile.Trajectories.Labeled.Count
    Markers = [Markers squeeze(matfile.Trajectories.Labeled.Data(ii,1:3,:))’];
end

%%% create virtual markers
vMarkers = createVirtualMarkers(matfile);

%%% add virtual markers
Markers = [Markers vMarkers.AllData];
MLabels = [matfile.Trajectories.Labeled.Labels vMarkers.Label];

%%videodata
VideoFrameRate = matfile.FrameRate;

% number of markers
nM = length(MLabels);

% video time
[nvF, nc] = size(Markers);
vFrms = [1:nvF]’;
vTime = 1/VideoFrameRate*(vFrms);


% trim data region of interest by time if indicated
if isfield(tInfo, ‘Tstart’)
    t1 = tInfo.Tstart;
    t2 = tInfo.Tend;
    % get corresponding indices in video (markers), force and analog data
    vInds = find(vTime >= t1 & vTime <= t2);
    % fInds = find(fTime >= t1 & fTime <= t2);
    % aInds = find(aTime >= t1 & aTime <= t2);

    % trim the Marker data
    vFrms = vFrms(vInds);
    nvF = length(vFrms);
    vTime = vTime(vInds);
    Markers = Markers(vInds,:);

 end
```

```
rot90aboutX = [1 0 0;  0 0 1; 0 -1 0];
% If the coordinate frame does not have FY as vertical
    Markers = rot3DVectors(rot90aboutX, Markers);

err = writeMarkersToTRC(trcfile, Markers, MLabels, VideoFrameRate, vFrms, vTime,
'mm');
```

ConvertMATtoTRCandMOT.m

```
function err = convertMATtoTRCandMOT(matfile, trcfile, motfile, tInfo, stepDect)
% Convert .mat data file to .trc and .mot for OpenSim
% USAGE: error = convertMATtoTRCandMOT(matfile, trcfile, motfile)

%%==================== get Markerdata from Matfile =================
%%% put markers in correct format for writeMarkersToTRC
Markers = [];
for ii = 1:matfile.Trajectories.Labeled.Count
    Markers = [Markers squeeze(matfile.Trajectories.Labeled.Data(ii,1:3,:))'];
end

%%videodata
VideoFrameRate = matfile.FrameRate;

%%% force data
ForceData = matfile.Force; % 4 forceplates
ForceLabels = {"Fx", "Fy", "Fz"};
ForceUnits = "mm";
ForceFrameRate = matfile.Force(1).Frequency;

% number of markers
nM = matfile.Trajectories.Labeled.Count;

% video time
[nvF, nc] = size(Markers);
vFrms = [1:nvF]';
vTime = 1/VideoFrameRate*(vFrms);

% force data time
[nfF, nc] = size(ForceData(1).Force');
fFrms = [1:nfF]';
fTime = 1/ForceFrameRate*(fFrms);

% trim data region of interest by time if indicated

if isfield(tInfo, 'Tstart')
    t1 = tInfo.Tstart;
    t2 = tInfo.Tend;
    % get corresponding indices in video (markers), force and analog data
    vInds = find(vTime >= t1 & vTime <= t2);
    fInds = find(fTime >= t1 & fTime <= t2);
    % aInds = find(aTime >= t1 & aTime <= t2);

    % trim the Marker data
    vFrms = vFrms(vInds);
    nvF = length(vFrms);
    vTime = vTime(vInds);
```

```
    Markers = Markers(vInds,:);

    % trim the force data
    fFrms = fFrms(fInds);
    nfF = length(fFrms);
    fTime = fTime(fInds);
    for i = 1:numel(ForceData)
        ForceData(i).Force = ForceData(i).Force(:,fInds);
        ForceData(i).Moment = ForceData(i).Moment(:,fInds);
        ForceData(i).COP = ForceData(i).COP(:,fInds);
   end
end


%%fill gaps in marker trajectories
[missInds, missCols] = find(isnan(Markers) == 1);
uniqueCols = unique(missCols);
missMarks = ~mod(uniqueCols,3).*uniqueCols/3;
missMarks = missMarks(find(missMarks));
allInds = 1:size(Markers);
if any(missMarks)
    for I = missMarks'
        gapInds = missInds(find(missCols == 3*I));
        missLabel = matfile.Trajectories.Labeled.Labels(I);
        message = sprintf('Marker %s has %d frames missing.', missLabel{1},
length(gapInds));
        warning(message);

        if length(gapInds)<30
        % interpolate
         disp(['Interpolating gap for Marker ', missLabel{1}]);
         goodInds = setdiff(allInds, gapInds);
         gapVals = interp1(goodInds, Markers(goodInds, 3*I-2:3*I), gapInds,
'spline');
         Markers(gapInds,3*I-2:3*I) = gapVals;
        end
    end
end

%filter Markers
MarkersFilt = smooth4th(Markers, 6, VideoFrameRate);

%%% create virtual markers
MLabels = [matfile.Trajectories.Labeled.Labels];

rot90aboutX = [1 0 0;  0 0 1; 0 -1 0];
% If the coordinate frame does not have FY as vertical
    MarkersFilt = rot3DVectors(rot90aboutX, MarkersFilt);
```

```
err = writeMarkersToTRC(trcfile, MarkersFilt, MLabels, VideoFrameRate, vFrms,
vTime, 'mm');

%======================== Start Processing GRFs
==============================
%% plot unfilterd force data
disp(numel(tInfo.FP))
disp(tInfo.FP);
disp(tInfo.FP{1});
disp(tInfo.FP{2});

subplotsize = numel(tInfo.FP)
for ii = 1:numel(tInfo.FP)
    disp(ii)
    figure(1); subplot(1,subplotsize,ii); hold on; plot(ForceData(tInfo.FP{ii}).
Force'/80.5, 'LineWidth',3);
    title("GRF FP-" + string(tInfo.FP(ii)) + " (" + tInfo.limb(ii) + ")") ;hold
off;
    figure(2); subplot(1,subplotsize,ii); hold on; plot(ForceData(tInfo.FP{ii}).
COP', 'LineWidth',3);

   title("COP FP-" + string(tInfo.FP(ii)) + " (" + tInfo.limb(ii) + ")");hold
off;
    figure(3); subplot(1,subplotsize,ii); hold on; plot(ForceData(tInfo.FP{ii}).
Moment'/80.5, 'LineWidth',3);
    title("Moment FP-" + string(tInfo.FP(ii)) + " (" + tInfo.limb(ii) + ")")
;hold off;
end

% power spectrum of FP vertical (column3)
y = fft(ForceData(1).Force(3,:)); % 4 was 3
f = (0:nfF-1)*(ForceFrameRate/nfF);     % frequency range
pow = abs(y).^2/nfF;    % power of the DFT
figure(4); plot(f,pow), title('power vertical force plate 1');
axis([0 250 0 inf]);

%%% filter force data
F_cutOff = 15;

for i = 1:numel(tInfo.FP) %EDIT LUUK: added loop, row 1 and 2 were always emp-
ty.
    ForceDataFilt(i).Force = smooth(ForceData(i).Force', F_cutOff, ForceFrameRa-
te);
    ForceDataFilt(i).COP = smooth(ForceData(i).COP', F_cutOff, ForceFrameRate);
    ForceDataFilt(i).Moment = smooth(ForceData(i).Moment', F_cutOff, ForceFrame-
Rate);
end
```

```
%% plot filltered force data
for ii = 1:numel(tInfo.FP)
    figure(1); subplot(1,subplotsize,ii); hold on; plot(ForceDataFilt(ii).For-
ce/80.5, 'LineWidth',3); title("GRF FP-" + string(tInfo.FP(ii)) + " (" + tInfo.
limb(ii) + ")") ; hold off;
    figure(2); subplot(1,subplotsize,ii); hold on; plot(ForceDataFilt(ii).COP,
'LineWidth',3);title("COP FP-" + string(tInfo.FP(ii)) + " (" + tInfo.limb(ii) +
")");
    figure(3); subplot(1,subplotsize,ii); hold on; plot(ForceDataFilt(ii).Mo-
ment/80.5, 'LineWidth',3); title("Moment FP-" + string(tInfo.FP(ii)) + " (" +
tInfo.limb(ii) + ")") ; hold off;
end

%%% step detection for L & R
if stepDect >0
    steprange= [1 115 229];
    for Side = 1:2
        for ii = 1:2
            kk = find(contains(MLabels, append(tInfo.limb(Side), "_CaL")), 1,
'first');
            figure(6); subplot 211; hold on; plot(MarkersFilt(:, kk*3-1)); tit-
le(['Ankle Y' , string(tInfo.limb(Side))])
            [M, II]=min(MarkersFilt(steprange(ii):steprange(ii+1), kk*3-1));
            II = II-3;
            xline(II+steprange(ii));
            hold off;
            subplot 212; hold on; plot(-ForceDataFilt(tInfo.FP{Side}).For-
ce(:,3)); % 4 was 3
            xline((II+steprange(ii))*5);
            Hstrikes(Side, ii) = ([II+steprange(ii)]);
        end

       fprintf('%s step HS-HS t = %4.2f-%4.2f, length step %4.0f indices
\n',...
            string(tInfo.limb(Side)), vTime(Hstrikes(Side, 1)), vTime(Hstri-
kes(Side, 2)), (Hstrikes(Side,2)-Hstrikes(Side,1)));

    end
end
writeGRFsToMOT(ForceDataFilt, fTime(1), ForceFrameRate, append('grf_',motfile),
0, tInfo);
```

CreateVirtualMarkers.m

```
function VirtualMarkers = createVirtualMarkers(markerData, Mlabels)

%%% Mid_PSIS = (L_PSIS + R_PSIS)/2
L_PSIS = markerData(:,find(contains(Mlabels, 'L_PSIS'))*[3 3 3]+[-2 -1 0])';
R_PSIS = markerData(:,find(contains(Mlabels, 'R_PSIS'))*[3 3 3]+[-2 -1 0])';

Mid_PSIS = (L_PSIS + R_PSIS)./2;

VirtualMarkers.Label{1} = 'Mid_PSIS';
VirtualMarkers.Data{1} = Mid_PSIS;


%%% Mid_ASIS = (L_ASIS + R_ASIS)/2
L_ASIS = markerData(:,find(contains(Mlabels, 'L_ASIS'))*[3 3 3]+[-2 -1 0])';
R_ASIS = markerData(:,find(contains(Mlabels, 'R_ASIS'))*[3 3 3]+[-2 -1 0])';

Mid_ASIS = (L_ASIS + R_ASIS)./2;

VirtualMarkers.Label{2} = 'Mid_ASIS';
VirtualMarkers.Data{2} = Mid_ASIS;

%%% L_HJC & R_HJC (use Harringtonmethod)
[R_HJC, L_HJC]=HJCHarrington(L_ASIS, R_ASIS, L_PSIS, R_PSIS);

VirtualMarkers.Label{3} = 'L_HJC';
VirtualMarkers.Data{3} = L_HJC';
VirtualMarkers.Label{4} = 'R_HJC';
VirtualMarkers.Data{4} = R_HJC';

%%% Mid_HJC = (L_HJC + R_HJC)/2
Mid_HJC = (L_HJC + R_HJC)./2;

VirtualMarkers.Label{5} = 'Mid_HJC';
VirtualMarkers.Data{5} = Mid_HJC;

%%% Mid_Pelvis = (Mid_ASIS + Mid_PSIS)/2
Mid_Pelvis = (Mid_ASIS + Mid_PSIS)./2;

VirtualMarkers.Label{6} = 'Mid_Pelvis';
VirtualMarkers.Data{6} = Mid_Pelvis;

%%% L_KJC = (L_LEC + L_MEC)/2 (same for R)
L_LEC = markerData(:,find(contains(Mlabels, 'L_LEC'))*[3 3 3]+[-2 -1 0])';
L_MEC = markerData(:,find(contains(Mlabels, 'L_MEC'))*[3 3 3]+[-2 -1 0])';
R_LEC = markerData(:,find(contains(Mlabels, 'R_LEC'))*[3 3 3]+[-2 -1 0])';
R_MEC = markerData(:,find(contains(Mlabels, 'R_MEC'))*[3 3 3]+[-2 -1 0])';
```

```
L_KJC = (L_LEC + L_MEC)./2;
R_KJC = (R_LEC + R_MEC)./2;

VirtualMarkers.Label{7} = 'L_KJC';
VirtualMarkers.Data{7} = L_KJC;
VirtualMarkers.Label{8} = 'R_KJC';
VirtualMarkers.Data{8} = R_KJC;

%%% L_AJC = (L_LM + L_MM)/2 (same for R)
L_LM = markerData(:,find(contains(Mlabels, 'L_LM'))*[3 3 3]+[-2 -1 0])';
L_MM = markerData(:,find(contains(Mlabels, 'L_MM'))*[3 3 3]+[-2 -1 0])';
R_LM = markerData(:,find(contains(Mlabels, 'R_LM'))*[3 3 3]+[-2 -1 0])';
R_MM = markerData(:,find(contains(Mlabels, 'R_MM'))*[3 3 3]+[-2 -1 0])';

L_AJC = (L_LM + L_MM)./2;
R_AJC = (R_LM + R_MM)./2;

VirtualMarkers.Label{9} = 'L_AJC';
VirtualMarkers.Data{9} = L_AJC;
VirtualMarkers.Label{10} = 'R_AJC';
VirtualMarkers.Data{10} = R_AJC;

%%% proj_L_AJC = (same for R)
proj_L_AJC = [R_AJC(1,:); L_AJC(2,:); zeros(size(L_AJC(1,:)))];
proj_R_AJC = [R_AJC(1,:); R_AJC(2,:); zeros(size(R_AJC(1,:)))];

VirtualMarkers.Label{11} = 'proj_L_AJC';
VirtualMarkers.Data{11} = proj_L_AJC;
VirtualMarkers.Label{12} = 'proj_R_AJC';
VirtualMarkers.Data{12} = proj_R_AJC;

%%% proj_L_CaL = (same for R)
L_CaL = markerData(:,find(contains(Mlabels, 'L_CaL'))*[3 3 3]+[-2 -1 0])';
R_CaL = markerData(:,find(contains(Mlabels, 'R_CaL'))*[3 3 3]+[-2 -1 0])';

proj_L_CaL = [L_CaL(1,:); L_CaL(2,:); zeros(size(L_CaL(1,:)))];
proj_R_CaL = [R_CaL(1,:); R_CaL(2,:); zeros(size(R_CaL(1,:)))];

VirtualMarkers.Label{13} = 'proj_L_CaL';
VirtualMarkers.Data{13} = proj_L_CaL;
VirtualMarkers.Label{14} = 'proj_R_CaL';
VirtualMarkers.Data{14} = proj_R_CaL;

%%% proj_L_Mt1 (same for R)
L_Mt1 = markerData(:,find(contains(Mlabels, 'L_Mt1'))*[3 3 3]+[-2 -1 0])';
R_Mt1 = markerData(:,find(contains(Mlabels, 'R_Mt1'))*[3 3 3]+[-2 -1 0])';

proj_L_Mt1 = [L_Mt1(1,:); L_Mt1(2,:); zeros(size(L_Mt1(1,:)))];
proj_R_Mt1 = [R_Mt1(1,:); R_Mt1(2,:); zeros(size(R_Mt1(1,:)))];
```

```
VirtualMarkers.Label{15} = 'proj_L_Mt1';
VirtualMarkers.Data{15} = proj_L_Mt1;
VirtualMarkers.Label{16} = 'proj_R_Mt1';
VirtualMarkers.Data{16} = proj_R_Mt1;

%%% proj_L_Mt5 (same for R)
L_Mt5 = markerData(:,find(contains(Mlabels, 'L_Mt5'))*[3 3 3]+[-2 -1 0])';
R_Mt5 = markerData(:,find(contains(Mlabels, 'R_Mt5'))*[3 3 3]+[-2 -1 0])';

proj_L_Mt5 = [L_Mt5(1,:); L_Mt5(2,:); zeros(size(L_Mt5(1,:)))];
proj_R_Mt5 = [R_Mt5(1,:); R_Mt5(2,:); zeros(size(R_Mt5(1,:)))];

VirtualMarkers.Label{17} = 'proj_L_Mt5';
VirtualMarkers.Data{17} = proj_L_Mt5;
VirtualMarkers.Label{18} = 'proj_R_Mt5';
VirtualMarkers.Data{18} = proj_R_Mt5;

%%% proj_L_MidToe = (proj_L_Mt1 + proj_L_Mt5)/2
proj_L_MidToe = (proj_L_Mt1 + proj_L_Mt5)./2;
proj_R_MidToe = (proj_R_Mt1 + proj_R_Mt5)./2;

VirtualMarkers.Label{19} = 'proj_L_MidToe';
VirtualMarkers.Data{19} = proj_L_MidToe;
VirtualMarkers.Label{20} = 'proj_R_MidToe';
VirtualMarkers.Data{20} = proj_R_MidToe;

%
VirtualMarkers.AllData = [Mid_PSIS'  Mid_ASIS'   L_HJC   R_HJC   Mid_HJC...
    Mid_Pelvis'  R_KJC'  L_KJC'  L_AJC'   R_AJC'  proj_L_AJC'  proj_R_AJC'...
    proj_R_CaL'  proj_L_CaL'  proj_R_Mt1'     proj_L_Mt1'   proj_R_Mt5'  pro-
j_L_Mt5'...
    proj_R_MidToe'    proj_L_MidToe'];
```

HJCHarrington.m

```
function [RHJC, LHJC]=HJCHarrington(LASIS, RASIS, LPSIS, RPSIS)
%Hip joint center computation according to Harrington et al J.Biomech 2006

for t=1:size(RASIS,2)

    %Right-handed Pelvis reference system definition
    SACRUM(:,t)=(RPSIS(:,t)+LPSIS(:,t))/2;
    %Global Pelvis Center position
    OP(:,t)=(LASIS(:,t)+RASIS(:,t))/2;

    PROVV(:,t)=(RASIS(:,t)-SACRUM(:,t))/norm(RASIS(:,t)-SACRUM(:,t));
    IB(:,t)=(RASIS(:,t)-LASIS(:,t))/norm(RASIS(:,t)-LASIS(:,t));

    KB(:,t)=cross(IB(:,t),PROVV(:,t));
    KB(:,t)=KB(:,t)/norm(KB(:,t));

    JB(:,t)=cross(KB(:,t),IB(:,t));
    JB(:,t)=JB(:,t)/norm(JB(:,t));

    OB(:,t)=OP(:,t);

    %rotation+ traslation in homogeneous coordinates (4x4)
    pelvis(:,:,t)=[IB(:,t) JB(:,t) KB(:,t) OB(:,t);
                   0 0 0 1];

    %Trasformation into pelvis coordinate system (CS)
    OPB(:,t)=inv(pelvis(:,:,t))*[OB(:,t);1];

    PW(t)=norm(RASIS(:,t)-LASIS(:,t));
    PD(t)=norm(SACRUM(:,t)-OP(:,t));

    %Harrington formulae (starting from pelvis center)
    diff_ap(t)=-0.24*PD(t)-9.9;
    diff_v(t)=-0.30*PW(t)-10.9;
    diff_ml(t)=0.33*PW(t)+7.3;

    %vector that must be subtract to OP to obtain hjc in pelvis CS
    %vett_diff_pelvis_sx(:,t)=[-diff_ml(t);diff_v(t);diff_ap(t);1];
    %vett_diff_pelvis_dx(:,t)=[diff_ml(t);diff_v(t);diff_ap(t);1];
    vett_diff_pelvis_sx(:,t)=[-diff_ml(t);diff_ap(t);diff_v(t);1];
    vett_diff_pelvis_dx(:,t)=[diff_ml(t);diff_ap(t);diff_v(t);1];

    %hjc in pelvis CS (4x4)
    rhjc_pelvis(:,t)=OPB(:,t)+vett_diff_pelvis_dx(:,t);
    lhjc_pelvis(:,t)=OPB(:,t)+vett_diff_pelvis_sx(:,t);
```

```
    %Transformation Local to Global
    RHJC(:,t)=pelvis(1:3,1:3,t)*[rhjc_pelvis(1:3,t)]+OB(:,t);
    LHJC(:,t)=pelvis(1:3,1:3,t)*[lhjc_pelvis(1:3,t)]+OB(:,t);

end

RHJC=RHJC';
LHJC=LHJC';


Readtrc.m
function [data, header] = readtrc(filename)
%READTRC Reads traces in a .trc file from a Rohde & Schwarz device
fid = fopen(filename, 'r');

if fid == -1
        error('Cannot open the file.');
    end

    % Read the header (the first 6 lines typically contain header information)
    header = textscan(fid, '%s', 6, 'Delimiter', '\n');
    header = header{1};

    % Read the actual data
    data = textscan(fid, '%f %f %f %f %f %f %f %f %f', 'HeaderLines', 6, 'Deli-
miter', '\t');
    fclose(fid);
end
```

Rot3DVectors.m

```
function rotated = rot3DVectors(rot, vecTrajs)
% Rotate any N number of 3D points/vectors
% USAGE: rotated = rot3DVectors(rot, vecTrajs)
%        rot is 3x3 rotation matrix
%        vecTrajs, Matrix of 3D trajectories (i.e. ntime x 3N cols)
% Ajay Seth

[nt, nc] = size(vecTrajs);

if rem(nc,3),
    error('Input trajectories must have 3 components each.');
end

for I = 1:nc/3,
    vecTrajs(:,3*I-2:3*I) = [rot*vecTrajs(:,3*I-2:3*I)']';
end

rotated = vecTrajs;
```

Smooth.m

```
% smooth.m
% Smooth data using a 2nd order lowpass.
% Usage: Y = smooth(data, cutOff, sampleFreq)
% Ajay Seth

function Y = smooth(data, Wc, sFreq)

maxF = sFreq/2;

wn = Wc/maxF;

[NF, Nc] = size(data);

[B, A] = butter(2, wn);


for I = 1:Nc,
    y = filtfilt(B, A, data(:,I));
    Y(:,I) = y;
end

% smooth.m
% Smooth data using a 2nd order lowpass.
% Usage: Y = smooth(data, cutOff, sampleFreq)
% Ajay Seth

function Y = smooth4th(data, Wc, sFreq)

% Define filter parameters
fs = 1000; % Sampling frequency
fc = 50; % Cutoff frequency
wn = fc / (fs/2); % Normalize cutoff frequency

maxF = sFreq/2;

wn = Wc/maxF;

[NF, Nc] = size(data);

% Design Butterworth filter coefficients
[B, A] = butter(4, wn);

% Apply the filter using filter function
for I = 1:Nc,
    y = filtfilt(B, A, data(:,I));
    Y(:,I) = y;
end
```

Write_MotionFile.m

```
function write_motionFile(q, fname)

fid = fopen(fname, 'w');
if fid == -1
      error(['unable to open ', fname])
end

if length(q.labels) ~= size(q.data,2)
      error('Number of labels doesn''t match number of columns')
end

if q.labels{1} ~= 'time'
      error('Expected ''time'' as first column')
end

fprintf(fid, 'name %s\n', fname);
fprintf(fid, 'datacolumns %d\n', size(q.data,2));
fprintf(fid, 'datarows %d\n', size(q.data,1));
fprintf(fid, 'range %f %f\n', min(q.data(:,1)), max(q.data(:,1)));
fprintf(fid, 'endheader\n');

for i=1:length(q.labels)
      fprintf(fid, '%20s\t', q.labels{i});
end
fprintf(fid, '\n');

for i=1:size(q.data,1)
      fprintf(fid, '%20.8f\t', q.data(i,:));
      fprintf(fid, '\n');
end

fclose(fid);
return;
```

WriteGRFsToMOT.m

```
function [] = writeGRFsToMOT(GRFTz, tStart, sF, fname, isFZ, tInfo)
% Purpose:  Write ground reaction forces applied at COP to a
%           motion file (fname) for input into the SimTrack
%           workflow.
%
% Generate column labels for forces, COPs, and vertical torques.
% Order:  rGRF(xyz), rCOP(xyz), lGRF(xyz), lCOP(xyz), rT(xyz), lT(xyz)
label{1} = ‘r_ground_force_vx’;
label{2} = ‘r_ground_force_vy’;
label{3} = ‘r_ground_force_vz’;
label{4} = ‘r_ground_force_px’;
label{5} = ‘r_ground_force_py’;
label{6} = ‘r_ground_force_pz’;
label{7} = ‘l_ground_force_vx’;
label{8} = ‘l_ground_force_vy’;
label{9} = ‘l_ground_force_vz’;
label{10} = ‘l_ground_force_px’;
label{11} = ‘l_ground_force_py’;
label{12} = ‘l_ground_force_pz’;
label{13} = ‘r_ground_torque_x’;
label{14} = ‘r_ground_torque_y’;
label{15} = ‘r_ground_torque_z’;
label{16} = ‘l_ground_torque_x’;
label{17} = ‘l_ground_torque_y’;
label{18} = ‘l_ground_torque_z’;

% Initialize ‘motion file data matrix’ for writing data of interest.

nRows = length(GRFTz(1).Force);
nCols = length(label)+1;   % plus time
motData = zeros(nRows, nCols);

% Write time array to data matrix.
time = tStart:1/sF:(tStart + (nRows-1)/sF);
motData(:, 1) = time;

%%% extract FP data R
for jj = find(contains(tInfo.limb, ‘R’))
    numFP = tInfo.FP{jj};
    GRF_R_Force = GRFTz(numFP).Force;
    GRF_R_COP = GRFTz(numFP).COP.*0.001; %mm --> m
    GRF_R_Moment = GRFTz(numFP).Moment;
end

%%% extract FP data L
for jj = find(contains(tInfo.limb, ‘L’))
    numFP = tInfo.FP{jj};
```

```
    GRF_L_Force = GRFTz(numFP).Force;
    GRF_L_COP = GRFTz(numFP).COP.*0.001; %mm --> m
    GRF_L_Moment = GRFTz(numFP).Moment;
end

%transform GRF data
rot90aboutX = [1 0 0;  0 0 1; 0 -1 0];
rGRF_R_Force = -1*rot3DVectors(rot90aboutX, GRF_R_Force);
rGRF_R_COP = rot3DVectors(rot90aboutX, GRF_R_COP);
rGRF_R_Moment = -1*rot3DVectors(rot90aboutX, GRF_R_Moment);

rGRF_L_Force = -1*rot3DVectors(rot90aboutX, GRF_L_Force);
rGRF_L_COP = rot3DVectors(rot90aboutX, GRF_L_COP);
rGRF_L_Moment = -1*rot3DVectors(rot90aboutX, GRF_L_Moment);

% Write force data to data matrix.
% NOTE:  each field of mCS.forces has xyz components. -> after rotation!
%FP hits right leg = FP4, left leg = FP1
forceData = [rGRF_R_Force(:,1) rGRF_R_Force(:,2) rGRF_R_Force(:,3)...
            rGRF_R_COP(:,1) zeros(nRows,1) rGRF_R_COP(:,3)...
            rGRF_L_Force(:,1) rGRF_L_Force(:,2) rGRF_L_Force(:,3)...
            rGRF_L_COP(:,1) zeros(nRows,1) rGRF_L_COP(:,3)...
            zeros(nRows,1) rGRF_R_Moment(:,2) zeros(nRows,1) ...
            zeros(nRows,1) rGRF_L_Moment(:,2) zeros(nRows,1)];

motData(:, 2:end) = forceData;

% Open file for writing.
fid = fopen(fname, ‘w’);
if fid == -1
    error([‘unable to open ‘, fname])
end

% Write header.
fprintf(fid, ‘name %s\n’, fname);
fprintf(fid, ‘datacolumns %d\n’, nCols);
fprintf(fid, ‘datarows %d\n’, nRows);
fprintf(fid, ‘range %d %d\n’, time(1), time(nRows));
fprintf(fid, ‘endheader\n\n’);

% Write column labels.
fprintf(fid, ‘%20s\t’, ‘time’);
for i = 1:nCols-1
     fprintf(fid, ‘%20s\t’, label{i});
end

% Write data.
for i = 1:nRows
    fprintf(fid, ‘\n’);
```

```
      for j = 1:nCols
         fprintf(fid, '%20.8f\t', motData(i, j));
    end
end

fclose(fid);
return;
```

WriteMarkersToTRC.m

```
function err = writeMarkersToTRC(trcfile, Markers, MLabels, Rate, Frames, Time,
Units)
% Write 3D Markers trajectories (real or virtual) to a .trc file
% USAGE: error = writeMarkersToTRC(trcFile, Markers, MLabels, Rate, Frames,
Time, Units)

err = 0;
[nvF, nc] = size(Markers);
nM = length(MLabels);

if (nM >= nc/3),
    % Maybe more labels than we need
    nM = nc/3;
    MLabels = MLabels(1:nM);
else
    % number of labels does not correspond to the number of Markers
    error('number of labels does not correspond to the number of Markers');
    err = 1;
end

if isempty(Frames),
    vFrms = [1:nvF]';
    vTime = 1/Rate*(vFrms);
else
    if (length(Frames) ~= nvF),
        error('number of frames does not correspond to the length of Markers');
        err = 1;
    end
    vFrms = Frames;
    vTime = Time;
end

% Assemble Marker data for writing out to .trc file
data = [vFrms vTime Markers];


% Generate the header for the .trc file
fid = fopen(trcfile, 'wt');


fprintf(fid, 'PathFileType\t4\t(X/Y/Z)\t%s\n', trcfile);
fprintf(fid, 'DataRate\tCameraRate\tNumFrames\tNumMarkers\tUnits\tOrigDataRate\
tOrigDataStartFrame\tOrigNumFrames\n');
fprintf(fid, '%f\t%f\t%d\t%d\t%s\t%f\t%d\t%d\n', ...
    Rate, Rate, nvF, nM, Units, Rate, vFrms(1), vFrms(end));
fprintf(fid, 'Frame#\tTime');
for I = 1:nM,
```

```
    fprintf(fid,'\t\t%s', MLabels{I});
end
fprintf(fid, '\n\t\t');
for I = 1:nM,
    fprintf(fid,'\tX%i\tY%i\tZ%i', I,I,I);
end
fprintf(fid, '\n\n');

fclose(fid);

% Now append the data to the file now that header has been written out.
dlmwrite(trcfile, data, '-append', 'delimiter', '\t');
```

FPA_Measuring

```
% Clear workspace and command window
%regels veranderen: r. 6, r. 15, r. 40, r. 103
clear; clc;

% Define the filename of the data file (either .mat or .trc)
filename = 'Filename.mat'; % Change to 'data.trc' if using a .trc file

% Load the data based on the file extension
[~,~,ext] = fileparts(filename);

switch ext
    case '.mat'
        data = load(filename);
        % Access the nested structure
        labeled = data.filename.Trajectories.Labeled; %change filename
        % Display marker labels
        disp('Labels in the Labeled structure:');
        disp(labeled.Labels);
        % Find indices for the markers
        R_CaL_idx = find(strcmp(labeled.Labels, 'R_CaL'));
        R_Mt1_idx = find(strcmp(labeled.Labels, 'R_Mt1'));
        R_Mt5_idx = find(strcmp(labeled.Labels, 'R_Mt5'));

        % Inspect dimensions of the Data array
        dataSize = size(labeled.Data);
        disp('Dimensions of Data array:');
        disp(dataSize);

        % Check if indices are within bounds
        if max([R_CaL_idx, R_Mt1_idx, R_Mt5_idx]) > dataSize(1)
            error('Marker index exceeds data array bounds.');
        end

        % Extract marker data based on indices
        R_CaL = squeeze(labeled.Data(R_CaL_idx, 1:3, :))'; % Transpose to get
[time, x, y, z]
        R_Mt1 = squeeze(labeled.Data(R_Mt1_idx, 1:3, :))';
        R_Mt5 = squeeze(labeled.Data(R_Mt5_idx, 1:3, :))';

         % Assuming the data has a field for frame rate (Hz)
        frameRate = data.filename.FrameRate; % Adjust filename

    case '.trc'
        % Read .trc file using an appropriate function
        [trcData, trcHeader] = readTRC(filename);
        R_CaL = trcData(:, strcmp(trcHeader, 'R_CaL')); % Replace with actual
column names
```

```
        R_Mt1 = trcData(:, strcmp(trcHeader, 'R_Mt1')); % Replace with actual
column names
        R_Mt5 = trcData(:, strcmp(trcHeader, 'R_Mt5')); % Replace with actual
column names

    otherwise
        error('Unsupported file format.');
end

% Calculate the midpoint of R_Mt1 and R_Mt5
R_Mid = (R_Mt1 + R_Mt5) / 2;

% Calculate the vector from R_CaL to the midpoint
vector = R_Mid - R_CaL;

% Determine walking direction based on change in x-coordinate of R_CaL
walking_direction = sign(diff(R_CaL(:, 1)));
walking_direction = [walking_direction; walking_direction(end)]; % Append last
value to maintain length

% Calculate the foot progression angle
foot_progression_angle = atan2d(vector(:,2), vector(:,1)); % Angle with respect
to x-axis

% Adjust angles based on walking direction
adjusted_angle = foot_progression_angle;
adjusted_angle(walking_direction < 0) = mod(adjusted_angle(walking_direction <
0) + 180, 360) - 180;

% Calculate velocity
velocity = diff(R_CaL); % Adjust based on which marker is best for velocity cal-
culation
velocity_magnitude = sqrt(sum(velocity.^2, 2));

% Find moments when velocity is nearly zero
threshold = 0.5; % Define a suitable threshold for "nearly zero"
zero_velocity_indices = find(velocity_magnitude < threshold);

% Extract the foot progression angle at those moments
fpa_at_zero_velocity = foot_progression_angle(zero_velocity_indices);

% Calculate the corresponding times for zero velocity indices
time_at_zero_velocity = zero_velocity_indices / frameRate;

% Set limits for the foot progression angle
angle_lower_limit = -15; % Lower limit in degrees
angle_upper_limit = 15;  % Upper limit in degrees

% Filter the results based on the angle limits
```

```
valid_indices = (fpa_at_zero_velocity >= angle_lower_limit) & ...
                (fpa_at_zero_velocity <= angle_upper_limit);

filtered_fpa = fpa_at_zero_velocity(valid_indices);
filtered_time = time_at_zero_velocity(valid_indices);

% Create a table with the results
resultsTable = table(time_at_zero_velocity, fpa_at_zero_velocity, ...
                     'VariableNames', {'Time_seconds', 'Foot_Progression_An-
gle'});

% Define the output CSV filename
outputFilename = ['Filename_foot_progression_angle_results.csv']; %deze naam
veranderen als je dezelfde file nogmaals wilt runnen, anders error

% Save the table to a CSV file
writetable(resultsTable, outputFilename);


% Display the result
disp('Filtered Foot Progression Angle at Almost Zero Velocity:');
disp(filtered_fpa);
disp('Filtered Time at Almost Zero Velocity (seconds):');
disp(filtered_time);
%disp(['Filtered results have been saved to ', outputFilename]);

% Function to read .trc files
function [data, header] = readTRC(filename)
    fid = fopen(filename, 'r');
    for i = 1:3
        fgetl(fid); % Skip the first three lines
    end
    header = strsplit(fgetl(fid), '\t'); % Read header
    frameRate = 100; % Assuming frame rate is 100 Hz, change if necessary
    data = fscanf(fid, '%f'); % Read data
    data = reshape(data, [], numel(header)); % Reshape data
    fclose(fid);
end
```