



# **Motion-Capture Comparison of Unilateral and Bilateral Knee Orthoses in Orthopedic Rehabilitation**

Bachelor's Degree Project in Mechanical Engineering

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# Abstract

This thesis examines the contribution of orthosis, between having unilateral (support on one side of the knee) orthoses compared to bilateral (support on both sides of the knee) orthoses, to a patient's rehabilitation process following knee-related orthopedic injuries. Such as muscle weakness, anterior cruciate ligament (ACL) injuries, or impaired bone function resulting from surgical procedures or neurological diseases.

Since ethical guidelines restrict the use of patients with knee-related orthopedic injuries in this research. Therefore, only healthy subjects were recruited, and all tasks were within the normal range of motion. The analysis was done with Optical Motion Capture and biomechanical properties, allowing for a detailed analysis of the orthoses. The orthosis with support on both sides of the knee was the more stable option in 10 out of 12 comparisons. The results point to a clear trend: that the two-sided support is the most effective option in terms of control and stability.

This research provides insight into how well the orthoses contribute to rehabilitation and the potential it has in optimization of medical applications.

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# Terminology/ Abbreviations

QTM – Qualisys Track Manager

OMT – Optical Motion Tracking

LB – Lower Body

ACL - Anterior Cruciate Ligament

OMC – Qualisys Optical Motion Capture

LCS – Local Coordinate System

GCS – Global Coordinate System

3D – Three-Dimensional

2D – Two-Dimensional

# 1. Introduction

This thesis investigates how well orthosis contributes to a patient's rehabilitation process of knee-related orthopedic injuries. The study delves into the use of orthopedic orthoses. Both types of orthoses have unique functions, but at the same time share several common characteristics. The purpose of the study is to highlight which of the orthoses is best in the rehabilitation process of knee-related injuries.

## 1.1 Background

Orthoses are a growing technology with great potential in both industrial applications and healthcare. The need for this technology has existed for as long as humanity has existed, but it is only now, with today's technological advances and increased understanding, that we have the opportunity to develop and implement it on a broad front.

In healthcare, orthoses can play a crucial role for patients who have suffered from muscle weakness, nerve damage, or impaired bone function because of surgical procedures or neurological diseases. These patients may experience significant limitations in their mobility, which can affect their quality of life and prolong the rehabilitation process.

To meet these challenges, Chalmers Johanneberg and Sahlgrenska University Hospital are collaborating in a study on how orthoses can contribute to the rehabilitation of orthopedic injuries. Chalmers focuses on developing solutions that provide patients with muscle support and reduce the time required for rehabilitation. At the same time, they are exploring methods for testing orthoses in controlled environments without involving patients, as they have not yet received approval from Sahlgrenska University Hospital for clinical studies.

This research is an important step towards integrating orthoses into healthcare and may ultimately lead to improved treatment methods, increased mobility, and shorter rehabilitation times for patients.

## 1.2 Purpose

This project aims to analyze a robotic model of a knee joint to examine the difference between having support on one side of the knee and both sides of the knee, to keep the knee more stabilized and avoid misalignment in the knee.

Since ethical guidelines restrict the use of patients with knee injuries in this type of research, our solution offers a safe and realistic testing environment. By simulating healthy subjects' movement patterns with Optical Motion Capture and biomechanical properties. The model allows researchers to analyze and identify the orthosis that offers the greatest benefits before using it in clinical settings.

## 1.3 Goal

The goal is to investigate whether it is more advantageous to orthosis with one-sided support or two-sided support on the knee joint in the rehabilitation of knee injuries, with the aim of maximizing stability and control.

## 1.4 Delimitations

The project has established several constraints to focus more on what is relevant, given the limitations of time, money, resources, experience, and lack of in-depth knowledge of the problem. The constraints may vary between the different phases during the course of the project.

- The project budget is 5,232 SEK, with most of it allocated to creating a simple prototype for all models.
- The product must be able to withstand forces/loads on the orthosis.
- A lack of expertise and knowledge in both motion capture and programming.
- Lack of test subjects.
- Limited approaches for estimating misalignment.
- An orthosis that is not fully functional.

## 1.5 Clarification of the research question

- Does it make any difference to the rehabilitation process if the patient uses a knee orthosis that provides support on only one side of the knee joint (outside of the knee) compared to one that supports both sides of the knee?
- Which of the orthoses leads to minimal misalignment in the knee joint, in the frontal plane?
- Is the knee movement more limited in any of those situations?

## 2. Theory

### 2.1 Anterior cruciate ligament (ACL) injuries

Cruciate ligament injuries are one of the most serious and common knee injuries that can occur. Every year, approximately 8,000 people in Sweden suffer from a cruciate ligament injury, of which about half undergo surgery, according to data from the (Svenska Korsbandsregistret, 2025). The injury most often occurs in sports where drastic breaking or rapid changes of direction are made; these movements are most common in contact sports such as football, basketball, or handball. Most often, injury is caused by the body's movement mechanics, rather than direct contact; it can be a twisting, overextension, or a combination of both. (Kacprzak et al., 2024)

Cruciate ligament injury (ACL injury) entails a significantly increased risk of developing osteoarthritis in the knee joint. This risk remains regardless of whether the injury is surgically repaired or not. Despite this risk, a strong medical consensus exists that patients with functional knee joint instability who aim to resume sports should undergo reconstruction of the cruciate ligaments. This highlights the importance of restoring knee joint stability to enable a return to high-intensity sports. Furthermore, ACL injury is a sport-related injury that leads to the highest rate of sports disability. This clearly illustrates its profound impact on athletes' careers and underlines the need for effective treatment and rehabilitation strategies (Waldron et al., 2022).

Exercise is one of the most critical factors in treating a knee injury to regain movement in the knee joint and reduce swelling. Neuromuscular training and balance training are gradually starting. Mobility training is prioritized initially. Strength training with external load begins as soon as the doctor and orthopedist give a clear signal. The training is progressive to help regain knee movement. Doctors provide a Knee orthosis that assists movement and provides support during the rehabilitation process. The knee orthosis is designed to help patients regain mobility and strength in the knee joint in a controlled and safe way. This can enable early mobilization and reduce the load on the knee, promoting healing and accelerating the process (Zhou et al., 2025).

### 2.2 Rehabilitation Orthoses

The development of technology in recent decades has enabled enormous progress in scientific fields such as rehabilitation, bionics, robotics, and medicine. This enormous progress is due to the integration of knowledge and techniques from the aforementioned fields.

Orthosis or rehabilitation exoskeleton is an example of interdisciplinary integration in the development of physiotherapeutic intervention tools, which is a training tool that

has shown significant results in patients with neurological diseases. The production of sophisticated and specifically designed knee orthoses took off during the 20th century, although simple supports for the knee joint can be traced back far in history. In the mid-20th century, orthoses were made of metal and became more and more common for use for weak bones and joints.

In 1967, Robert F. McDavid became the first person to develop the "modern" knee orthosis. The orthosis was designed to prevent injuries and aid in healing. In the same year, the design was tested on an American football player who had suffered a knee injury. This rehabilitation helped to increase awareness and acceptance of these aids in sports. This rehabilitation gained momentum after that, and in the 1970s, more and more prophylactic knee orthoses began to be tested and used by athletes with the aim of reducing the number of rehabilitation weeks (The Brief History of Knee Braces, 2014).

Knee braces are orthopedic aids that are applied externally to the affected area. Fixation is done via adjustable devices, such as Velcro or plastic buckles, which helps with individual adjustment (Barrera Sánchez et al., 2022). It is extremely important that the adjustments are correct if you want to have the desired stabilization. If the brace does not fit well enough or exerts unacceptable pressure, the therapeutic effectiveness can decrease and thus have a negative impact. The negative impact can lead to swelling or pain.

For optimal function and patient comfort, it is important to ensure that the brace is applied correctly. The selection of a suitable orthopedic aid should be made through expert consultation, a doctor, an orthopedist, or a specialist in orthopedic technology. This approach ensures an accurate assessment of the need and the optimal selection of orthotics.

The duration of use of braces varies depending on the patient's injury, as well as what the medical clinic deems suitable for the patient. During the treatment phase, it is extremely important that the patient follows the instructions and advice that the clinic has given. Using an orthosis during the night is uncommon but may be a requirement for special cases if the clinic has determined so.

If any discomfort with the orthosis occurs during use, an evaluation should be performed to identify and resolve the potential cause. The orthosis can be used for a while longer, even though the acute injury to the knee has healed. The orthosis is then used to prevent incorrect loading and to reduce the risk of overexertion. Today, orthoses are a huge part of many rehabilitation protocols, as Team Olmed (n.d.) outlines their ability to:

- Reduce pain.
- Increase stability.
- Control movement.
- Protect healing tissues.
- Early mobilization.
- Enable a gradual return to activity.
- Prevent injuries from recurring.

### 2.2.1 Recovery period

Rehabilitation for an ACL injury is a long process, lasting 6 to 12 months. However, sometimes it can take longer to return to normal activity levels. This depends largely on the individual; people with a sporting background tend to recover more quickly than others. The rehabilitation process has phases that gradually increase in intensity and complexity. (Massachusetts General Brigham Sports Medicine, 2021).

- During the first two weeks, the focus is on reducing the swelling and pain in the knee. Crutches are used to regain mobility and normalize walking patterns with the aid.
- Weeks 3 to 6 focus on gradually achieving full extension in the knee joint and beginning lighter muscle activation transitions. As well as gradually ending crutches, here the focus is also on reducing swelling and pain.
- The intermediate phase, weeks 6 to 12, is to intensify strength training of the muscles around the knee joint, mainly the quadriceps and hamstrings. In addition, training in neuromuscular control and balance is required. It should be added that even lighter cardio training on a bicycle or a cross trainer is common at this stage.
- Months 3 to 6 are when the goal is to continue building strength, neuromuscular control, and endurance. More functional exercises and lighter runs can be started at this stage.
- 6 to 12 months is the time to return to normal, which may include sport-specific training that gradually increases load and assesses the knee's function in relation to the uninjured side. Return to full contact sports is usually recommended only

after at least 9 to 12 months, after certain criteria are met and full mobility in the knee has returned without any swelling or pain in the knee.

The rehabilitation time depends a lot on the person and on certain factors such as the severity of the injury, whether surgery has been performed, the patient's commitment and willingness to participate in rehabilitation, the individual's previous activity level and their individual healing ability.

## 2.3 Orthopedic and neurological exoskeleton

Active and passive exoskeletons have become very important in orthopedic and neurorehabilitation. Passive exoskeletons, which refer to orthoses, are more commonly used in orthopedic injuries. While Active exoskeletons have sensors and actuators to assist or control movement. Technology improves motor function, increases independence, and promotes recovery in patients who have suffered neurological injuries or musculoskeletal disorders. Neuro- and orthopedic orthoses differ in applications and design principles.

### 2.3.1 Neurological exoskeleton

Neurorehabilitation is done to regain movement and function. The orthosis in neurorehabilitation is primarily aimed at people who have experienced traumatic brain injuries, stroke, spinal cord injury or cerebral palsy (Cui et al., 2023). Experiences that are characterized by impaired motor control, paresis, or plegia. The goals of the exoskeletons are to facilitate motor relearning through assistance and guided movement, balance and walking ability, reduce spasticity and increase joint mobility and simulate neuroplasticity, the brain's ability to reorganize itself.

Technology in neurorehabilitation exoskeleton strives to apply the principle of "assist-as-needed, where support is only given when needed and dynamically adapts according to the patient's movement inertia. This is possible because the control system uses sensors, such as electromyography (EMG), which measures muscle activity, force sensors and angle sensors (Maceira-Elvira et al., 2019).

### 2.3.2 Orthopedic exoskeleton

Orthopedic rehabilitation is to support healing and regain mobility. The orthosis in Orthopedic rehabilitation is primarily aimed at people with musculoskeletal injuries or osteoarthritis, fractures or ligament injuries, as well as patients who have undergone

orthopedic surgery. The goals of the orthosis are to ease the load on painful joints, improve mobility and function, stabilize unstable areas and support early mobilization and prevent further injuries by correcting incorrect loads.

Orthopedic orthoses refer to passive systems, which use mechanical elements to relieve and provide support without external power sources. The design focuses on supporting the knee and is often joint-specific. Ease of use and comfort are central aspects, as the orthosis is usually used for a longer period of time.

### 2.3.3 Orthoses with one-sided and two-sided support

The development of exoskeletons for knee rehabilitation led to designs with support on both the inner and outer sides of the knee. This was to optimize stability, especially around the knee joint. Through the support structures, the orthosis offered stability in the frontal plane, which is crucial for controlling adduction and abduction movements. (Movements closer to the body's midline, and away from the body's midline, respectively). The design minimized unwanted movements such as rotation in the knee joint. The exoskeleton's power transmission provided a more natural and effective assistance with knee flexion and extension during walking and other activities (Barrera Sánchez et al., 2022).

The orthosis design takes into account the complex biomechanics of the knee joint to ensure a compliant and correct movement between the orthosis and the knee. Orthoses have many important areas of application in rehabilitation; recovery from ligament injuries in the knee is something that orthoses greatly help with. The orthosis offers support and stability that are important in early mobilization and gradual return to activity. Orthoses with bilateral (two-sided) support can reduce the load on the damaged joint surface by distributing forces and stabilizing the joint laterally. Above all, the orthosis increases the patient's safety during rehabilitation. It should be taken into account that the design is complex, the need for a comfortable and precise fit, and the risk of a potential increase in weight and size that may accompany more support structures.

Orthosis with support only on the outside of the knee, with the aim of addressing biomechanical challenges related to stability and misalignments in the frontal plane of the knee joint. The model is designed to provide targeted correction and support for conditions involving varus or valgus angulation. Such as Genu Valgum (balloting) in children (ortobas, [2019-07.19]). See Figure 1.

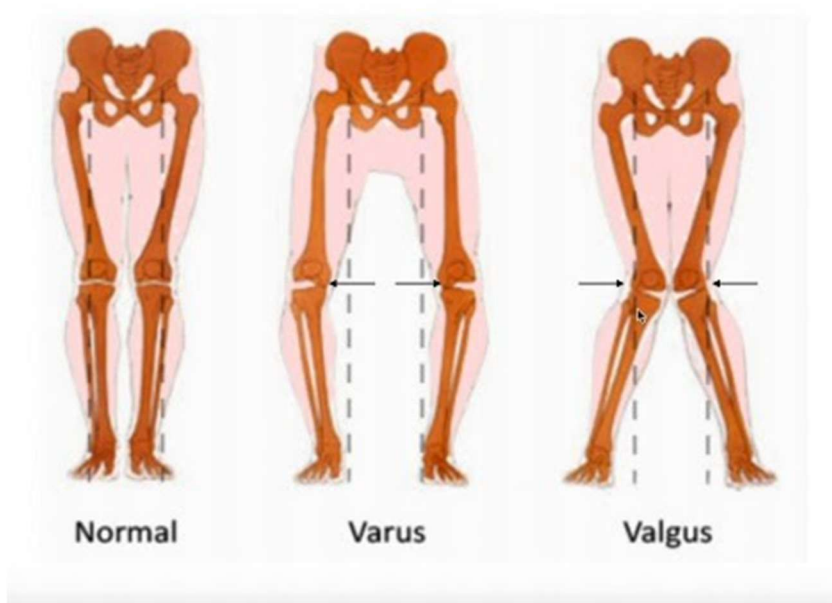


Figure 1 – normal position of the knee, outward angulation of the knee (Varus), respectively, inward angulation of the knee (Valgus)

## 2.4 Previous research and technology in exoskeletons

The development of orthoses for knee rehabilitation has undergone significant progression, from assistive movement to a sophisticated system integrated into the rehabilitation protocol. The focus of previous research has been on demonstrating that orthoses facilitate walking and movement, particularly in neurorehabilitation (Byl, 2012). Biomechanical analyses have measured changes in walking patterns and load distribution, contributing to an increased understanding of the interaction between the human and the exoskeleton. Increased focus on energy efficiency, user-friendliness, and adaptive control systems that respond to the patient's movement intentions. Clinical studies focus on the functional outcomes of training with orthoses, as well as the potential and need for further optimization (Dzidotor et al., 2023).

Comparisons of the inherent stability of unilateral (one-sided support) versus bilateral (two-sided support) orthoses for the knee joint during dynamic activities are few. Previous studies have analyzed the biomechanical effects of different orthosis designs and evaluated the functional outcomes of training; however, there is a lack of studies that primarily focus on comparing and quantifying stability aspects, such as lateral stability, rotational stability, and their impact on overall postural control. Patients' subjective experience of control and security with different systems is also an area that has not been investigated in comparative studies.

By directly comparing the stability analysis of unilateral and bilateral orthoses for the legs, this scientific text adds new and critical information to the field. The comparison

between unilateral and bilateral orthoses has the potential to provide a scientifically sound understanding of which design principles best optimize stability during orthosis-assisted movement. The results inform future design choices, development of better rehabilitation protocols, and facilitate clinical decisions. By addressing this knowledge gap with information and results, this scientific text contributes to maximizing the safety and benefit of orthosis technology in rehabilitation.

## 2.5 Optical motion capture (OMC)

Optical Motion Capture is a method that can record the movements of people or objects and convert these movements into 3D data. In rehabilitation science, OMC offers a scientific basis for analyzing and quantifying human movement. OMC contributes to a clearer understanding of movement patterns, compensation strategies, and the effects of various interventions, including the use of orthoses.

### 2.5.1 OMC in rehabilitation

Quantification of movement within OMC, the system uses cameras that track the reflective markers that are placed on the object or body. By triangulating from multiple camera angles simultaneously, an accurate 3D representation of the movement is created. OMC provides quantitative data on joint angles, axes, velocities, accelerations and other biomechanical parameters. The system can also capture subtle deviations in movement patterns that may otherwise be difficult to notice.

This is particularly valuable when analyzing patients with injuries where compensatory movements in other joints may occur. Evaluation of intervention effects, movement analyses before, during, and after a rehabilitation intervention, such as the use of a knee orthosis. The measurement assesses the effect of the intervention on the patient's mobility. Including whether orthosis improves stability and mobility. OMC is used by clinicians for gait analysis. The system can generate a detailed list of step length, step frequency, ground contact time, and joint angles during the gait cycle. This makes it easier for the clinician to identify pathological gait patterns and evaluate the effect of orthoses.

Real-time data from OMC can provide patients with visual feedback on how their movement is during exercise. This facilitates the correction of incorrect movement patterns and can help patients improve their motor skills, which is good for learning the correct movement with or without an orthosis. Technology is constantly evolving, and Optical Motion Capture (OMC) is no exception. OMC is an important tool in biomechanical research that focuses on better understanding the body's motor skills,

injury mechanisms and the effect of different rehabilitation strategies and various aids such as orthoses.

## 2.6 Projection

Projection is extremely useful in applications and fields such as computer graphics, engineering domains, statistics and signal processing. Quantification of movement within OMC utilizes projection to convert high-dimensional data into lower dimensions. This facilitates interpretation and analysis.

Projection is sort of like a vector. It can be mapped onto a plane, casting the light and seeing where the shadow lands; any lower-dimensional subspaces are doable.

Projection is intrinsically tied to the dot product of vectors. Because of how the dot product works, you could think of the dot product as what you get if you project one vector in the direction of another, and then multiply their lengths. Projection is a linear transformation; it can be represented as a matrix vector multiplication. This means that if we start with a column vector, then there's some projection matrix that you can multiply the vector on the left and the result will be the projected column vector if the vector is called  $X$  and then multiplying by some projection matrix that will call  $P$  to get the projected result that I'll call  $X$  hat, an alternative way to picture what the matrix is doing is to imagine starting with a vector in every point in space and seeing how they all get projected down on a plane. To project a vector " $V$ " onto a plane, we will need two basis vectors to span this plane, and we will call them  $x$  and  $y$ . These will essentially form the coordinate system for a plane. Will again suppose that we know the components of all three of these vectors, and therefore, we can find the lengths and angles between them too. The projection of  $V$ , which we can again call  $P$ , is going to lie somewhere in this plane. It may not be perfectly in line with either  $X$  or  $Y$ . Still, what we can do though, is express  $P$  as a linear combination of  $X$  and  $Y$ , what we're looking for then our components along those base directions, and then these add up to give us the full projection as an equation we can write  $P$ .

$$P = P_x X + P_y Y \quad (1)$$

There is a vector by taking our original vector  $V$  and subtracting the projection  $P$ . This vector  $V$  minus  $P$  is again referred to as the rejection vector. It is orthogonal to  $P$ , actually not just that it's going to be orthogonal to the plane in general, and  $V$  minus  $P$  is perpendicular to the plane. It's also going to be perpendicular to every vector in the plane, including  $X$  and  $Y$ . So we can get two equations by taking the dot product of this vector with  $X$  and the dot product of the vector  $Y$  and setting them both to 0 to represent that they should be perpendicular.

$$(v - P) \cdot x = 0$$

$$(v - P) \cdot y = 0$$

We get these by simplify  $x \cdot P = x \cdot v$  and  $y \cdot P = y \cdot v$  and substituting in for p gives;

$$x \cdot (P_x X + P_y Y) = x \cdot v \quad (2)$$

$$y \cdot (P_x X + P_y Y) = y \cdot v \quad (3)$$

Full generality, considering our X and Y basis vectors to be at 90°, but now we will let them point in any crazy direction and will let them have any length, we do still need the basis vectors to span the plane. So they can't be right on top of each other or outside the surface but otherwise, anything goes. Although the projected vector P is still going to be the same, its components in terms of the basis vector will be more complicated now. If there's a non-90 ° angle, then the components that would add up to P are not going to be orthogonal projections anymore. But we can still find them using the same method. Will consider the rejection vector, which is still perpendicular to both X and Y. So, we can write out our two normal equations.

$$(v - P) \cdot x = 0, \quad (v - P) \cdot y = 0$$

We can still break our projected vector down as a sum of components along X and Y. And substituting that in gives this, distributing the product gives us the full equations again. But this time, unfortunately nothing is going to cancel.

As shown in Equations (2 and 3), it is a system of two linear equations with two unknowns, which are the components of P, fortunately there's a standard linear algebra approach for dealing with these collected terms into matrices and then solving. The matrix terminology of dot products between our basis vectors is called the gram matrix. Tensor calculus is closely related to the idea of the metric tensor. What matters is that the equation can be solved by inverting this matrix. Before that, the dot-products must be translated back into the language of matrix multiplication, then factoring can be done.

Now by using our matrix A, which once again has X on one column and Y on the other, we can condense some more. Then invert the term on the far left to solve for our projection components, and finally plug these back in to get our projected vector. Start with the formula for the projection and factor it into matrix form. The first term is A, and then substitute in our components. The  $A^T$  inverse term in the middle is our normal term dealing with the fact that our basis factors X and Y are not orthonormal, then the outer terms A and  $A^T$  form the outer product. We could now do this in higher

dimensions, projecting onto hyperplanes instead of just planes, but we don't need to walk through it again because everything works out the same.

Formula projection matrix:

$$P = A(A^T A)^{-1} A^T v \quad (4)$$

### 3. Method Description

We first examined previous projects similar to the two models we were planning to use, observing what previous solutions looked like and why they were effective. These orthoses could have double-sided or single-sided support. Then, an idea generation process for materials and their design for optimal use was conducted, followed by a design in CAD and a prototype.

Using a prototype, the theory of the best solution between the two different models was tested on a single test subject throughout the whole project. The test was carried out via Optical Motion Capture, where we were able to test the different orthoses and saw which one could contribute to potentially give the best results for the rehabilitation of orthopedic injuries.

Using data from Optical Motion Capture, we could discover which model contributed to the least misalignment of the knee joint during the gait cycle. The reason we chose Optical Motion Capture was that the technology provides precise 3D measurements of the knee joint position and orientation, which is crucial for biomechanical analysis. Also, with the help of Optical Motion Capture, it was possible to calculate the distance between the knees and the orthosis and thus analyze how the distance varied during the gait cycle. To advance the analysis, misalignment in the knees and orthosis could be calculated by measuring the maximum angular deviation in the different planes during lateral and medial knee movement. This could then be compared between orthoses with two-sided support and one-sided support.

In addition, Optical Motion Capture is a non-invasive method, which means that during the process, the subject does not need to attach physical sensors to the skin, which leads to a smoother and more realistic movement.

## 4. Setup and Development

### 4.1 System Knowledge

Before the trials and data calculation could be conducted, a deep understanding of OMC and prior knowledge was required. The system used for OMC was the Qualisys motion capture system, which included the QTM software for calculation and registration of movements. The knowledge necessary to get started with the system included navigation in Qualisys, camera calibration, understanding and handling data from QTM, calculating the misalignment between knee and orthoses in horizontal axis using QTM, exporting data to MATLAB for plotting box plots, placing markers according to biomechanical standards, and applying a skeletal model for a clearer illustration of the 3D model.

### 4.2 prototype

To conduct practical tests with orthoses with one-sided knee support and the two-sided knee support, a simple prototype was required.

For the simple prototype, a CAD design was created. Since the primary focus was not on the prototype, a simple prototype was constructed, as shown in Figure 2. In addition, metal was chosen as the material for the components to achieve the criteria:

- High strength
- Rigidity
- Wear resistance and long life
- Precision machining
- Possibility of thin but strong structures



*Figure 2 - Simple prototype of metal exoskeleton (not finished).*

After almost completing the prototype, it was realized that the simple prototype would not be able to provide the project with the level of scientific accuracy and realism required. However, the prototype could be used for backup.

Instead, a knee orthosis with the necessary functions was borrowed, where the orthosis could be applied with supports on both sides of the knee (two-sided orthosis) or support only on one side (outer side) of the knee (one-sided orthosis). See figure 3.

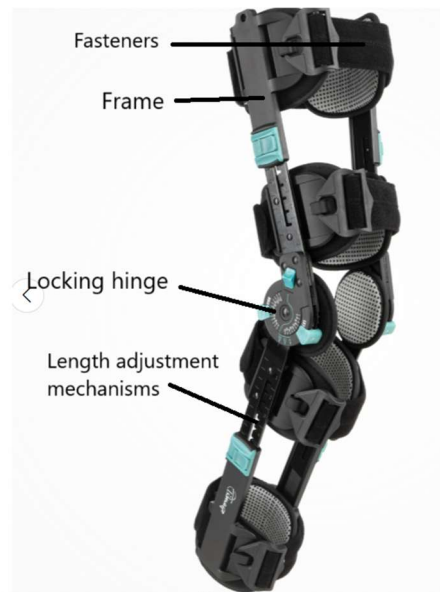


Figure 3 - Knee orthosis and its main components

### 4.3 Qualisys

To obtain accurate data for each test, a camera calibration was performed on the Qualisys system, which served as the basis for all tests. Calibration is performed by positioning the cameras to cover the entire volume of movement and aligning them towards the center, ensuring there are no blind zones. Then, place a calibration frame (L frame) in the middle of the work area to identify scaling, axis directions, and the origin of the 3D coordinate system. Then, move a calibration frame with markers (wand) to the area where the test is to be performed. This process is necessary for the cameras to calibrate themselves. This allows for the registration of markers in QTM, enabling the calculation of the exact orientation and position of each camera in the room.

When the calibration is complete, the residual value (error margin in millimeters) should be checked. The lower the residual value it shows, the more accurate the visual position of the markers is in relation to the actual position in the 3D space. The residual is recommended to be below 1 mm. Interference and wrong camera angles lead to a high error margin. Calibration of the cameras was performed regularly, particularly when their position was changed, to ensure accurate data. In addition, the Qualisys system tells you when a new calibration is needed.

## 5. Test

Before any test could begin, clear and standardized test conditions had to be established. It is a fundamental aspect of experimental research, especially in biomechanics. As a result, it leads to high-quality data collection by ensuring that every trial is performed under the same conditions.

### 5.1 Test conditions

In total, three different tests were carried out, each test corresponding to a selected position in the gait cycle. See Figure 4.

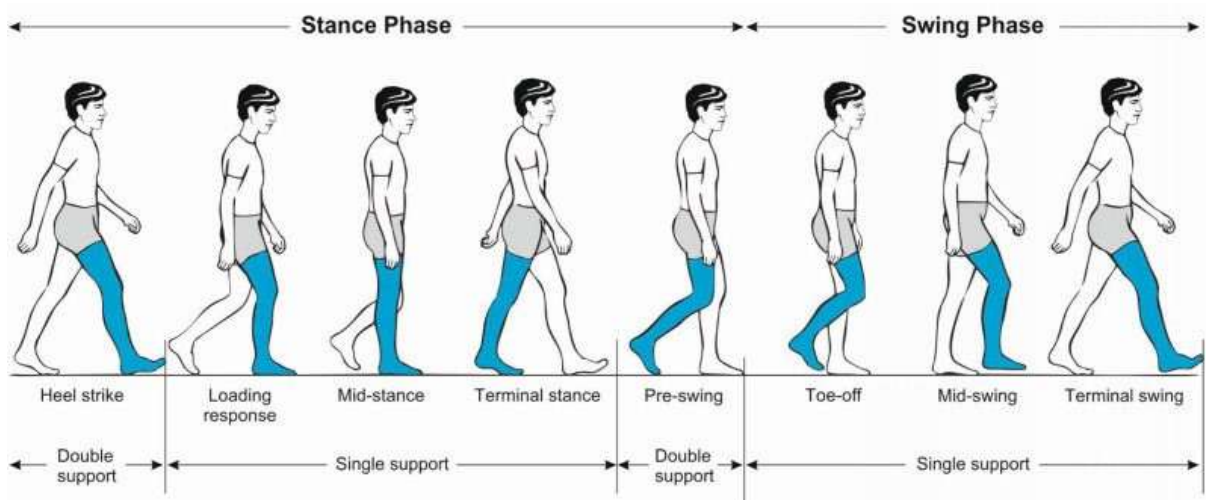


Figure 4 – Gait cycle. The colored leg (blue) is the targeted leg.

The three positions chosen in the gait cycle were the following:

- Loading response, when the entire sole is in contact with the ground. See Figure 5.
- Mid-stance, the non-targeted leg was also in a vertical position beside the targeted leg (blue color), see Figure 4.
- Terminal stance, when the entire sole is in contact with the ground. See Figure 5.

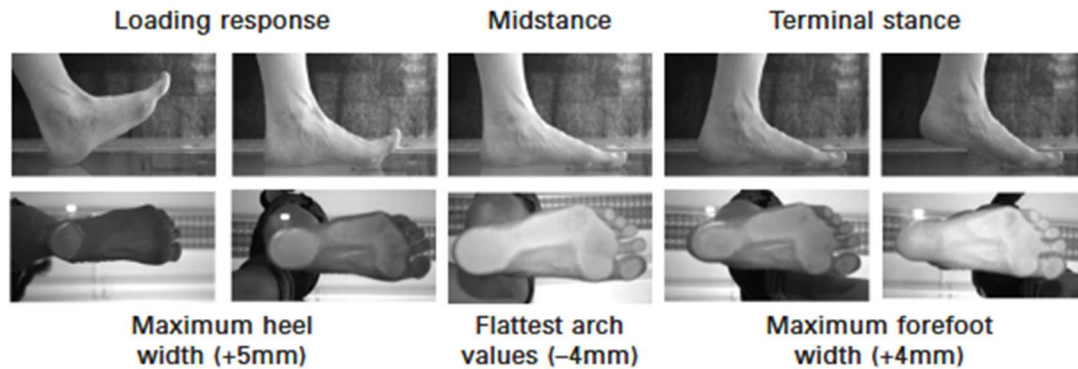


Figure 5 - Illustration of sole contact with the ground during the stance phase of the gait cycle.

Common conditions that were determined for all three different tests were:

- The entire sole is in contact with the ground throughout the exercise.
- Same stride length during loading response and terminal stance.
- Same knee angle for all three exercises.

### 5.1.1 Sole contact with the ground.

In all three different positions, the entire sole should be in contact with the ground. See figure 6, position (ii). This means that the heel should not be in contact with the ground while the toe is pointing upwards and, in the air, or vice versa. See figure 6 positions (i and iii). The reason is that when the entire sole is not in contact with the ground, the knees have greater freedom to move side to side compared to when the whole sole is in contact with the ground. To obtain optimized data, the conditions must be the same for all tests.

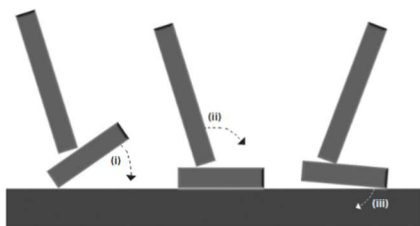


Figure 6 – Illustration of the position of the sole in relation to the surface.

### 5.1.2 Stride length

A study was conducted to calculate the average stride length for the Loading response and Terminal stance. According to (Physiopedia et al., 2025), the average stride length is 70 cm, depending on age and height. This value was acceptable because the purpose of

having a specific stride length was to have the same conditions between all exercises. This led to all exercises being performed at an exact 70 cm stride length, both in loading response and terminal stance.

### 5.1.3 Knee angle

Another decisive factor in obtaining concrete data was the knee angle and its impact on knee movement in both medial and lateral directions. The knee orthosis used in the tests had the function of locking itself at a specific angle using a mechanical locking mechanism at the knee joint. This enabled the tests to be carried out under a controlled biomechanical condition where the same knee angle could be used during all the tests.

According to the literature (Physiopedia et al., 2025), the largest angle created during the stance phase of a gait cycle is during the loading response. This occurs immediately after the heel has met the ground. During this phase, the knee angle is approximately 15 degrees. The 15-degree angle represents knee flexion from the fully extended (0°) position. It should not be interpreted as the absolute angle between the femur and tibia, but rather the degree of bending initiated from a straight leg posture. However, in the terminal stance and mid-stance phases, the knee angle is close to zero as the knees come close to full extension. See Figure 4.

To have a margin of error, considering that the knee angle varies depending on the person, a standard angle of 20 and 40 degrees was chosen when all exercises were performed. See Figure 7.



Figure 7 - 20 degrees (locking hinges)

Although mid-stances and terminal stances typically have no angle or an angle very close to zero, we chose to apply 20 degrees of bending in these moments as well in the test context. The reason behind this was that when the knee joint is fully extended, the knee movement locks in the medial and lateral directions (side to side), meaning that

the knee's movement side to side is limited to nearly complete locking. This, in turn, means that the tests do not have the same conditions. This factor was relevant, considering that the purpose of the tests is precisely to assess the misalignment between the horizontal axis of the knee and the knee orthosis, specifically when examining the orthosis with one-sided and two-sided support at the knees.

Biomechanically, the greater the knee angle, the greater the freedom of movement in the knee when it comes to movement in the medial and lateral directions. This means that patients who have suffered from muscle weakness, nerve damage, or impaired leg function due to surgical procedures or neurological diseases are more vulnerable to movements where the knee joint angle is large, particularly when it is close to fully flexed. Since more degrees of freedom in the medial and lateral planes of the knee joint lead to an increased risk of knees ending up in either varus (bow-legged) or valgus (knock-kneed) positions, see figure 1. This, in turn, leads to adverse outcomes such as increased risk of injury, extended rehabilitation time, and so on.

## 5.2 Pre-Test preparation

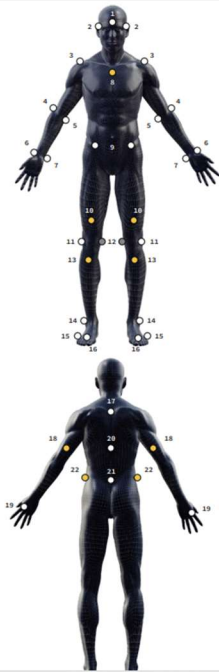
After the conditions were set for all the tests, it was time to start preparing for the tests. The preparation began with the participant placing the markers on their body. It was ensured that the markers were placed directly on the skin. And the body area where the markers were placed was dry and free of hair for optimal data precision. This resulted in minimal changes to the marker position during the body's movement.

The choice of marker set was made according to the project's needs, as there is no single marker set that is universally considered the most optimal in Qualisys. Instead, it is chosen depending on the type of tests that need to be done. And Qualisys allows any marker arrangement. However, for more reliable and consistent identification of anatomical landmarks, it is advisable to consult established references.

One such resource is the book "Color Atlas of Skeletal Landmark Definitions" by Serge van Sint Jan. This atlas provides detailed guidance on accurately locating and defining skeletal landmarks commonly used in biomechanical marker setups.

Referring to this source can enhance the precision of marker placement and contribute to improved repeatability in motion capture data. In this project, the Sports marker set was chosen as the standard model for how markers should be placed on the person (see Figure 8). However, markers were only placed on the lower part of the body, specifically in positions identified as LB (Lower Body), as shown in Figure 8. As the upper part of the body was not necessary.

### Detailed marker description



Display name	Location	Ref	Movable
1 HeadFront	Forehead, above the nose.	SGL	-
2 HeadL, HeadR	Just above the ear centre.	-	-
3 LShoulderTop, RShoulderTop	On top of the shoulder (bony prominence).	SAJ	-
4 LElbowOut, RElbowOut	On the outside of the elbow (bony prominence).	HLE	-
5 LElbowIn, RElbowIn	On the inside of the elbow (bony prominence).	HME	-
6 LWristIn, RWristIn	On the inside of the wrist (bony prominence on the thumb side).	RSP	-
7 LWristOut, RWristOut	On the outside of the wrist (bony prominence on the pinky side).	USP	-
8 Chest	Upper part of the sternum.	MSN	On the sternum
9 WaistLFront, WaistRFront	On the front of the pelvis (bony prominence).	IAS	-
10 LThighFrontLow, RThighFrontLow	Above the kneecap.	PAS	On the thigh
11 LKneeOut, RKneeOut	On the outside of the knee (bony prominence).	FLE	-
12 LKneelin, RKneelin	On the inside of the knee (bony prominence).	FME	-
13 LShinFrontHigh, RShinFrontHigh	Front of the shin.	TTC	On the shin
14 LAnkleOut, RAnkleOut	On the outside of the ankle.	FAL	-
15 LForefoot5, RForefoot5	On the base of the fifth toe.	FT5	-
16 LForefoot2, RForefoot2	On the base of the second toe.	FT2	-
17 SpineThoracic2	On the 2nd prominence below the biggest prominence on the top of the spine.	TV2	-
18 LArm, RArm	On the back of the upper arm.	HUM	On the upper arm
19 LHand2, RHand2	On the back of the hand at the base of the index finger.	HD2	-
20 SpineThoracic12	A few cm below the midpoint of the lower tip of the shoulder blades.	TV12	-
21 WaistBack	On the midpoint between the two prominences on the back of the pelvis.	SACR	-
22 WaistL, WaistR	On the sides of the pelvis (bony prominence).	ICT	On the pelvis
23 LHeelBack, RHeelBack	Back of the heel.	FCC	-

Figure 8 - Sports marker set: detailed description

Additionally, the number of markers can be increased as needed. The reason why the Sports marker set was chosen as standard was because of the following advantages:

- Optimal for freedom of movement:
  - The aim is to reduce marker collisions with each other and reduce gaps in data during fast movements.
  - Excellent for walking (Gait cycle).
- Standardized and approved configuration:
  - Often used in biomechanical studies and sports research, which allows for easier comparison of data and studies.
  - The QTM software features ready-made templates for smoother and accurate analysis.
- Few placements on soft tissue artefacts:
  - The position of the markers is well thought out and avoids points where movement artifacts are minor, and has its primary focus on anatomical points that are stable. Which refers to areas with minimal muscle between the skin and bone.
- Effective tracking and calibration:
  - The marker set has just the right amount of markers, enough for accurate tracking without being overloaded.

With the primary focus on the knee, the number of markers at the knees can be increased for an optimized result. The number of markers used during the tests was 31 in total, 21 on the lower body, and 5 markers on each side of the orthosis.

Markers on the skin, only markers identified as LB (Lower body), were used. In addition, markers were placed on both legs, even though only the right leg was equipped with a knee orthosis. The reason was to apply a “skeleton” to the 3D model in Qualisys for a clearer illustration of the lower body and to apply its function. See Figure 9.

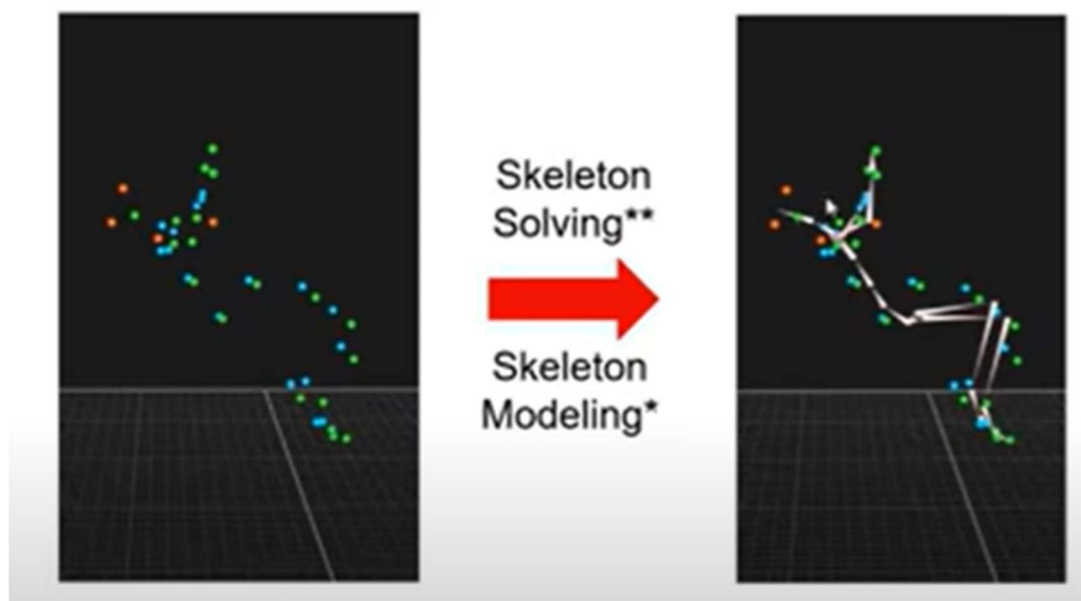


Figure 9 – Illustration of applied skeleton (right image)

Once the markers were positioned on the test subject, it was time to identify all markers by retrieving a ready-made template from QTM and then manually linking all names from the template with the markers that were displayed in the 3D window in Qualisys. See Figure 10

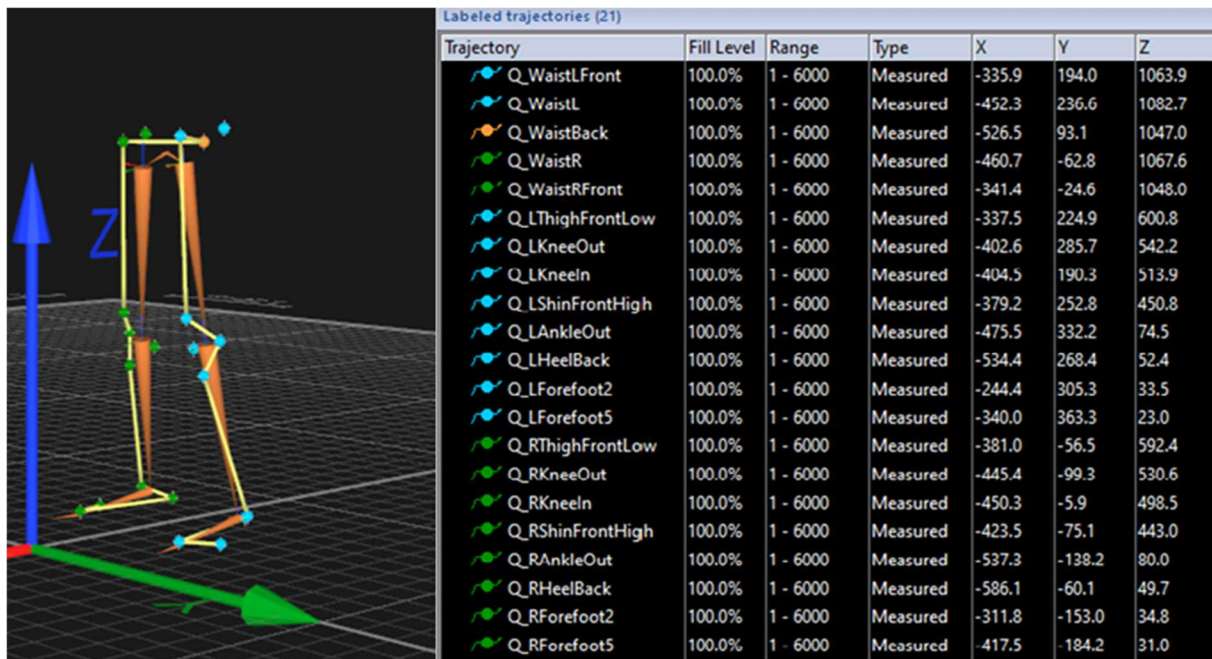


Figure 10 – Static position LB in Qualisys with a sports marker set.

### 5.3 Performed Tests

After the test subject had positioned all the markers, it was time to start the test. Each test was repeated across multiple trials to ensure accuracy. A single trial was defined as the sequence starting from a static position, followed by movement to the desired gait cycle position and performing the knee exercise, which involved moving the knee in lateral and medial directions 10 times while the whole sole is in contact with the surface. After which, the participant returned to the initial static position. The total trial in every exercise was 10 times, resulting in a total of 100 medial and lateral knee movements per exercise.

The breakdown of the exercises:

#### One-sided knee orthosis:

- Loading response at 20° knee flexion
- Mid-stance at 20° knee flexion
- Terminal stance at 20° knee flexion
- Loading response at 40° knee flexion
- Mid-stance at 40° knee flexion
- Terminal stance at 40° knee flexion

#### Two-sided knee orthoses:

- Loading response at 20° knee flexion
- Mid-stance at 20° knee flexion
- Terminal stance at 20° knee flexion
- Loading response at 40° knee flexion
- Mid-stance at 40° knee flexion
- Terminal stance at 40° knee flexion

Every test began with a static trial, where the participant stood in a T-pose (feet shoulder-width apart and arms extended). The purpose of the static trial is for the system to see and identify all the markers. See Figure 10.

Every exercise was captured (recorded) by the Qualisys Optical Motion Capture system and saved in a folder in the software. Whenever the participant was ready to perform an exercise, a second operator manually activated the capture function in the Qualisys software (QTM). The software started capturing data of the positioned markers on the participant. In contrast, the participant stood within the calibrated capture volume, where tapes were used for indicating the predefined stride length (70 cm) and correct foot placement. After completing the exercise, a second operator manually deactivated the capture. The data collected by the 12 Qualisys optical motion capture cameras, positioned around the testing area, was automatically saved in a file within the software and could be reviewed afterward.

## 6. Analysis Of Data from Qualisys

The OMC system records high-precision 3D positional data from the reflective markers placed on the participant during the test. The data collected is essential for biomechanical analysis, making it possible to quantify kinematic variables, such as calculating distances between anatomical landmarks and joint angles.

### 6.1 Data storage and management in Qualisys

During a motion capture trial using a Qualisys system, the 12 synchronized infrared cameras detect reflection from the markers and transmit their coordinates to QTM software in real time. The position of every marker is identified as a set of three Cartesian coordinates (x, y, z). Depending on the application, the software can be set to sample the data ranging from 100 Hz (hertz) to over 300 Hz. Due to the internal recommendation in the lab, it was set at 300 Hz, which means the markers' positions are calculated 300 times per second.

The data from each exercise is saved in a structured data file format (.c3d or .qtm file). The files include capture volume geometry, calibration parameters, and camera settings, making sure the data is accurate. The QTM software also provides the opportunity to export marker data into various formats, such as TSV, for use in MATLAB or Python.

The data stored in Qualisys is optimized for both accessibility and precision. Marker trajectories are saved frame by frame; one frame equals one Hz. An interpolation algorithm can be applied when gaps are detected in the dataset. This is to estimate marker positions during gaps to maintain the integrity of the dataset.

### 6.2 Converting the global coordinate system into a local coordinate system.

Before using the data to calculate the misalignment, the data collected in the global coordinate system (GCS) must be transformed into the local coordinate system (LCS). This is crucial, especially when analyzing a specific body part. In this case, the knee area is where computations relative to the local body part coordinate are more relevant and meaningful.

In QTM, this was applied by selecting markers associated with the knee and the orthosis (see Figure 11). To create a separate body, three markers are needed to identify the three axes. By identifying axes Z and Y, axis X was automatically recognized by the program.

The software QTM uses the following formula to transform the global coordinate system to the local coordinate system:

$$p' = R^T \cdot (p - B_0) \quad (5)$$

$p'$  = position vector in the LCS

$p$  = position in the GCS

$R^T$  = transpose of the rotation matrix, representing the orientation of the local frame relative to the global frame.

$B_0$  = translation vector, representing the origin of the local frame in global coordinates.

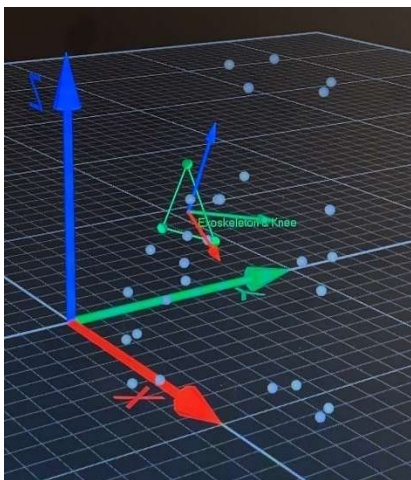


Figure 11 – LCS with respect to the GCS

### 6.3 Angle Calculation

In many biomechanical analyses, angles are defined by multiple markers arranged to show the anatomical axes or segments. Specifically, the angle created by two lines, each represented by markers, is a key parameter. This provides an understanding of joints, such as extension and flexion, as well as adduction and abduction. This method was used in this project to calculate the misalignment between the horizontal axis of the knee joint and the horizontal axis of the orthosis's joint. See Figure 12.

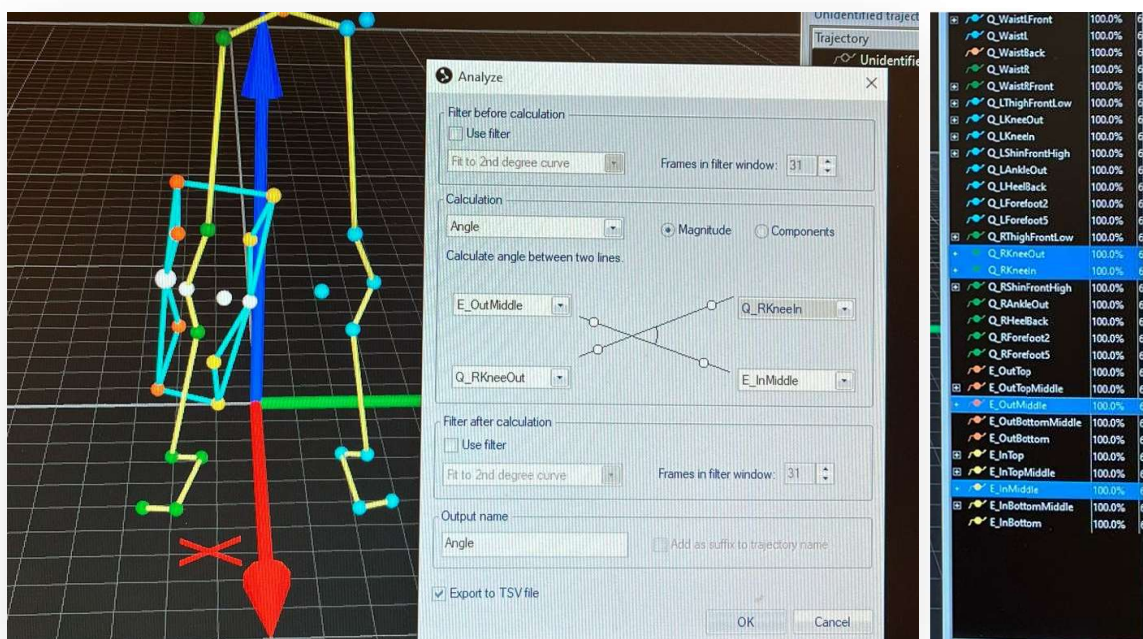


Figure 12 – identification of two lines with calculation of the angle between them on the orthosis with two-sided support

### 6.3.1 Orthosis with two-sided support:

As seen in Figure 12, the yellow line (bones) connecting the markers, including those markers without yellow lines, illustrates the lower body of the participants, based on the sports marker set. The markers connected by light blue lines represent the double-sided knee orthosis, which is placed on the knee.

The two markers selected (white markers), see Figure 12, on the participant's knee, involved in the first line formation and angle calculation, are:

**Q\_RKneeOut** = Outer side of the knee joint on the right knee.

**Q\_RkneeIn** = Inner side of the knee joint on the right knee.

They identify the outer and inner sides of the participant's knee joint. See Figure 12

The two markers selected (white markers) on the double-sided orthosis, see Figure 12, involved in the second line formation and angle calculation, are:

**E\_OutMiddle** = Outer joint of the orthosis.

**E\_InMiddle** = Inner joint of the orthosis.

They identify the outer and inner sides of the knee joint in the orthosis. See Figure 12

In Figure 12, line 1 is defined by marker Q\_RKneeOut and marker Q\_RkneeIn, and line 2 is defined by marker E\_OutMiddle and marker E\_InMiddle. By using the tool “Analyze” in QTM, the software calculated the angle between the two lines throughout the exercises. Meaning the total amount of angle data was equal to the amount of seconds multiplied by 300, since QTM registered markers’ position 300 times per second.

The exact formula used by Qualisys to calculate the angle couldn’t be found, but here is an illustration of how it could be calculated:

Consider two lines:

Line 1, defined by marker  $M_1$  (Q\_RKneeOut) and  $M_2$  (Q\_RkneeIn).

Line 2, defined by markers  $M_3$  (E\_OutMiddle) and  $M_4$  (E\_InMiddle).

The vectors creating these lines are:

$$\vec{v}_1 = M_2 - M_1 = (x_2 - x_1, y_2 - y_1, z_2 - z_1)$$

$$\vec{v}_2 = M_4 - M_3 = (x_4 - x_3, y_4 - y_3, z_4 - z_3)$$

The angle  $\theta_{\text{radians}}$  between these two vectors using the dot product formula:

$$\theta = \cos^{-1} \left( \frac{\vec{v}_1 \cdot \vec{v}_2}{|\vec{v}_1| |\vec{v}_2|} \right) \quad (6)$$

Where

$$\vec{v}_1 \cdot \vec{v}_2 = (x_2 - x_1)(x_4 - x_3) + (y_2 - y_1)(y_4 - y_3) + (z_2 - z_1)(z_4 - z_3)$$

And  $|\vec{v}|$  denotes the magnitude (length) of vector  $v$ :

$$|\vec{v}| = \sqrt{v_x^2 + v_y^2 + v_z^2}$$

This gives the angle  $\theta$  in radians in a specific frame. This can then be done for every frame throughout the whole exercise.

Changing the angle from radians to degrees happens through:

$$\theta_{\text{degrees}} = \theta_{\text{radians}} \cdot \frac{180}{\pi} \quad (7)$$

### 6.3.2 Orthosis with one-sided support:

As in the orthosis with two-sided support, markers with light blue connections represent the orthosis with one-sided support; see Figure 13. Due to only having single-sided support on the outer side of the knee, the marker (Q\_RKneeIn) positioned on the inner side of the knee had to be shared to create the two lines for calculating the angles. Markers involved in the first line formation and angle calculation for the participant's knee include:

$M_1$ : **Q\_RKneeOut** = Outer side of the knee joint on the right knee.

$M_2$ : **Q\_RKneeIn** = Inner side of the knee joint on the right knee.

The two selected (white markers), see Figure 13, involved in the second line formation and angle calculation include:

$M_3$ : **E\_OutMiddle** = Outer middle of the orthosis.

$M_2$ : **Q\_RKneeIn** = Inner side of the knee joint on the right knee.

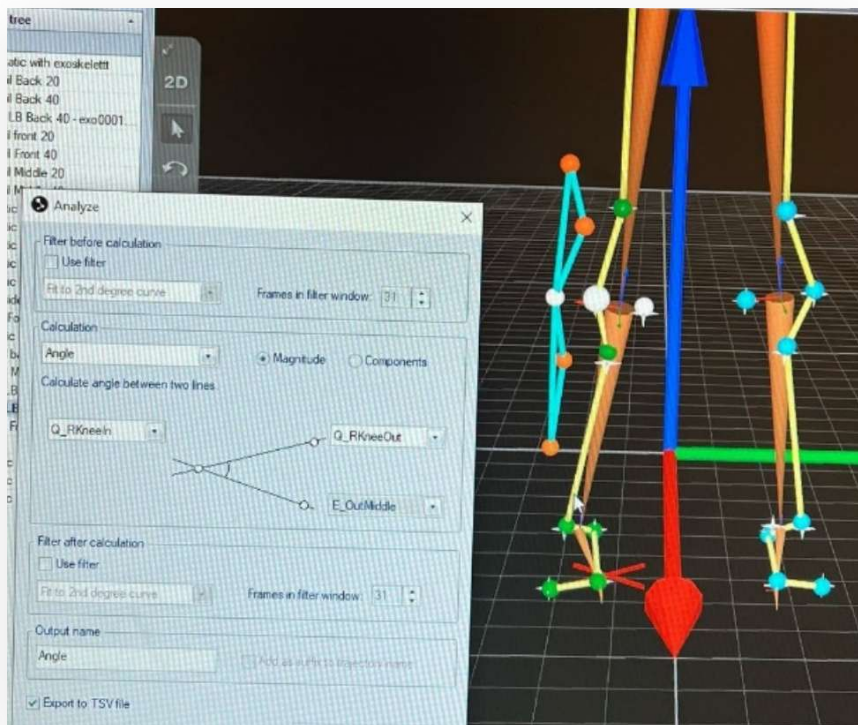


Figure 13 – identification of two lines with calculation of the angle between them on the orthosis with one-sided support

Similar to Section 6.3.1, the angle is calculated through identifying the two vectors by three markers

$$\vec{v}_1 = \vec{M}_1 - \vec{M}_2$$

$$\vec{v}_2 = \vec{M}_3 - \vec{M}_2$$

Calculation of the angle between the Vectors:

$$\theta = \cos^{-1} \left( \frac{\vec{v}_1 \cdot \vec{v}_2}{|\vec{v}_1| |\vec{v}_2|} \right) \quad (8)$$

Where:

$\vec{v}_1 \cdot \vec{v}_2$  is the dot product of the two vectors

$|\vec{v}_1| |\vec{v}_2|$  are the magnitudes of the vectors

As shown in Equation (7), angle is converted from radians to degrees.

## 6.4 Data filtering and noise reduction

To ensure the validity and reliability of the data analysis, it is essential to apply an appropriate filter to reduce noise. Applying too many filters risks losing important data. In any motion capture system, there are often various sources of noise. It can come from marker jitters, soft tissue artifacts, or camera calibration errors. In Qualisys, the filtering tools are:

- **Moving average smoothing:** Smooths local spikes or jitter by averaging marker coordinates over a specified window
- **Fit to 2<sup>nd</sup> degree curve:** it fits a quadratic polynomial (a second-degree curve) to a segment of data.

The filtering tools could be applied before and after calculating the data, and in both filtering tools, the window size can be set from 0 to 99 frames, depending on the level of smoothing aggressiveness. Applying more frames leads to more aggressive smoothing.

Window size = The number of frames used to create each new value.

In this project, before calculating the data and exporting the file to MATLAB, the filtering tool, moving average smoothing, was used to analyze the angle with a window size of 30, which is recommended for a sampling rate of 300 Hz. Both higher window sizes and filtering after data calculation were avoided because they led to the loss of essential data.

## 6.5 3D-to-2D Projection of Motion Capture Data

When analyzing different data in biomechanical studies, motion is typically referred to in anatomical planes: Transverse (horizontal), frontal, and sagittal planes. Even though the OMC system collected data in the third dimension (3D) space, it was crucial to project the motion data onto a corresponding two-dimensional (2D) plane. This was because the angle needed to calculate the misalignment in the horizontal knee joint and the horizontal knee orthosis joint had to be measured in the frontal and transverse planes. These planes are in 2D. The frontal plane was the primary focus during this thesis.

Qualisys provided a built-in tool called “Components”, which enabled the data to be reviewed in both frontal (YZ plane) and transverse (XY) planes (see Figure 14).

Detailed description of the process of projection of 3D to 2D, see Section 2.6.

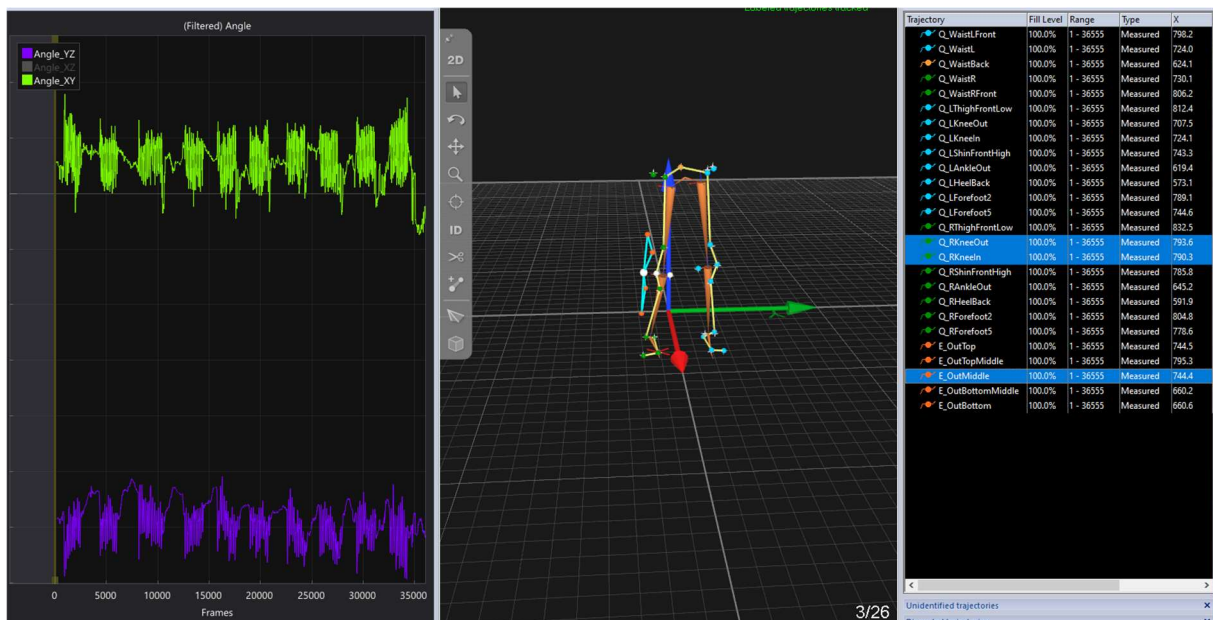


Figure 14 – Angle calculation (single-sided orthosis) in the frontal and transverse plane. The y-axis of the graph is angle (degrees), and the X-axis represents time (frames). 300 frames = 1 second

## 6.6 Export file and graph visualization

While Qualisys calculated the angle automatically, it provided the option to export the data through a TSV file for MATLAB or to create a graph showing angles in every frame and draw a line between the data points. For better illustrations, see figure 12.

All the data for the respective exercise was exported as a TSV file to MATLAB to create a statistical analysis.

## 6.7 Statistical analysis

For the statistical analysis, a boxplot, also known as a box-and-whisker plot, and diagrams were chosen. A boxplot is a graphical tool used to summarize the distribution of a dataset. It's crucial in a statistical analysis as it offers a compact and visual overview of the most critical dataset.

### **Advantages of using boxplots:**

- Simplicity and clarity
- Comparison across groups: in our case, orthosis with single-sided support and double-sided support.
- Detection of outliers: It visually highlights extreme or unusual values.
- No assumptions required: boxplots don't guess a normal distribution, unlike parametric tests, which makes them reliable and robust.
- Clear communication of results both to technical and non-technical audiences.

### **A boxplot typically displays:**

- Median: the central line inside the box, which represents the middle value
- Mean: average of all data points, more sensitive to extreme values or outliers.
- The interquartile range (IQR): the box expansion, from the first quartile (Q1) to the third quartile (Q3), showing the middle 50% of the data.
- Whiskers: lines extending from the box to the min and max value within  $1.5 \times \text{IQR}$ .
- Outliers: dots outside of the whiskers represent measurement errors or rare events that are important to identify.

### 6.7.1 Octave code

In order to efficiently process and analyze data exported from Qualisys, Octave-online was used to manage and analyze the exported data. Through custom-written scripts, the data was prepared and organized for statistical analysis. This included identifying, min/max value, median, mean, and IQR value, which was needed to create a boxplot.

```

1 % Load data from the file "front20xynew" % Make sure
  'front20xynew.txt' is in the same directory as your Octave
  script, % or provide the full path to the file. try if
  exist('front20xynew.txt', 'file') == 2 data = load
  ('front20xynew.txt'); else disp('Error: File "front20xynew
  .txt" not found. '); return; % Exit the script if the file
  is not found end catch ME disp('Error loading file
  "front20xynew.txt". '); disp(['Error message: ', ME.message]
  ); return; % Exit the script on error end
2
3 % Calculate the mean of the original data original_mean = mean
  (data);
4
5 % Subtract the original mean from all data points adjusted_data
  = data - original_mean;
6
7 % Calculate statistical measures for the adjusted data
  adjusted_mean = mean(adjusted_data); adjusted_std_dev = std
  (adjusted_data); adjusted_min_value = min(adjusted_data);
  adjusted_max_value = max(adjusted_data); adjusted_median =
  median(adjusted_data); q_adjusted = quantile(adjusted_data,
  [0.25, 0.75]); adjusted_iqr = q_adjusted(2) - q_adjusted(1
  );
8
9 % Display the results for the adjusted data disp(' '); % Empty
  line for better readability disp('=== Statistical Summary
  for front20xynew (Adjusted Data) ==='); disp(['Adjusted
  Mean: ', num2str(adjusted_mean)]); disp(['Adjusted Standard
  Deviation: ', num2str(adjusted_std_dev)]); disp(['Adjusted
  Minimum Value: ', num2str(adjusted_min_value)]); disp
  (['Adjusted Maximum Value: ', num2str(adjusted_max_value)]
  ); disp(['Adjusted Median: ', num2str(adjusted_median)]);
  disp(['Adjusted Interquartile Range: ', num2str
  (adjusted_iqr)]); disp(' '); % Empty line for better
  readability

```

Figure 15 – shows the cod in octave online for file front20xynew.

From Qualisys, many values were created, including 12 data for each plane, specifically the XY, YZ, and XZ planes. The 12 data were uploaded into Octave-Online, in the same directory as the Octave script. Then, a code was written in Octave that calculates the mean of the original data, `original_mean`, which is named `mean(data)`. Thereafter, it subtracts the original mean from all data points to get the new x-data. Following that, it calculates the statistical measures that are wanted for the latest data, "adjusted data". Then the code gives the value of mean, median, min, max, Interquartile Range (IQR), and the standard deviation for the "adjusted data". This was done for Loading Response, Mid-Stance, and Terminal Stance.

## 6.7.2 Google Colab code

```

import matplotlib.pyplot as plt
import numpy as np

# ---- USER INPUT ----
# Boxplot 1 values
min1 = -3.467
q1_1 = -2.486/2      # Q1 = Q2 - IQR/2
median1 = -0.6813
q3_1 = 2.486/2      # Q3 = Q2 + IQR/2
max1 = 4.52
mean1 = 0

# Boxplot 2 values
min2 = -2.02
q1_2 = -1.303/2
median2 = -0.1550
q3_2 = 1.303/2
max2 = 5.44
mean2 = 0

# Plot labels
plot_title = "Terminal-Stance, 40 degrees in YZ plane"
x_labels = ["One-sided", "Two-sided"]
y_label = "Misalignmnet (degrees)"

# ---- DESCRIPTION (English) ----
"""
This code creates two side-by-side boxplots using manually specified statistical values.
Boxplots are a way to graphically depict groups of numerical data through their five-number summary:
Minimum, First Quartile (Q1), Median (Q2), Third Quartile (Q3), and Maximum.
We also overlay the mean as a red dot on each boxplot for additional insight.
"""

# ---- CREATE CUSTOM BOX DATA ----
# The boxplot function expects a specific format, so we create dictionaries with the needed stats

# Define first boxplot values
box1 = {
    'whislo': min1, # Minimum value (lower whisker)
    'q1': q1_1, # First quartile (Q1)
    'med': median1, # Median (Q2)
    'q3': q3_1, # Third quartile (Q3)
    'whishi': max1, # Maximum value (upper whisker)
    'fliers': [] # No outliers
}

# Define second boxplot values
box2 = {
    'whislo': min2,
    'q1': q1_2,
    'med': median2,
    'q3': q3_2,
    'whishi': max2,
    'fliers': []
}

# Combine into a list for plotting
box_data = [box1, box2]

# ---- PLOTTING ----
fig, ax = plt.subplots()

# Create boxplots using pre-defined stats
ax.bxp(box_data, showfliers=False)

# Customize labels
ax.set_title(plot_title)
ax.set_ylabel(y_label)
ax.set_xticks([1, 2])
ax.set_xticklabels(x_labels)

# Add legend
ax.legend()

# Show the plot
plt.grid(True)
plt.show()

```

Figure 16 shows the code in Google Colab for plotting the box diagram.

Here is the Google Colab code that is used to plot the box diagram. Data from Octave Online provided statistics for both one-sided and two-sided support, including Mean, Standard Deviation, Minimum, Maximum, Median, and Interquartile Range. Then, certain characteristics are established, such as size and appearance. And then the diagram is plotted.

## 6.8 Knee orthosis with one-sided support and two-sided support

Overall, the two-sided support (bilateral orthosis ) showed lower IQR in 10/12 tested cases; the two exceptions were both in the XY plane. While in the YZ plane, which was our primary focus, 6/6 tests showed that two-sided support had a lower IQR.

### Loading Response, 20 degrees in XY plane (One-sided vs two-sided)

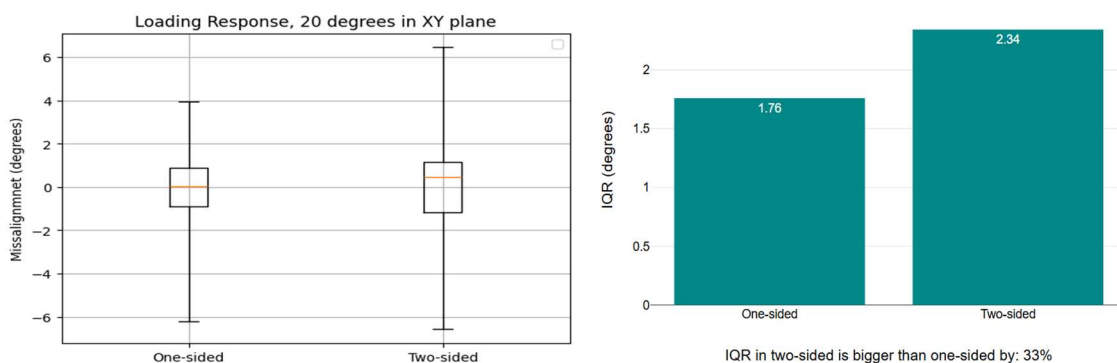


Figure 17—shows the misalignment in Loading Response

The standard deviation is lower for one-sided orthosis (1.6679) than for two-sided orthosis, which has a standard deviation of 2.2078. The max/min for front data is a range of about 10.2 (-6.21 to 3.97) for one-sided orthosis, while two-sided orthosis has a range of about 13.04 (-6.58 to 6.46). The interquartile range for one-sided orthosis (1.759) is shorter than the interquartile range for two-sided orthosis (2.342). The median for one-sided orthosis and two-sided orthosis is (0.0194 vs 0.4736). The spread is most extensive in the orthosis with two-sided support.

**Loading Response, 20 degrees in YZ plane (One-sided vs two-sided)**

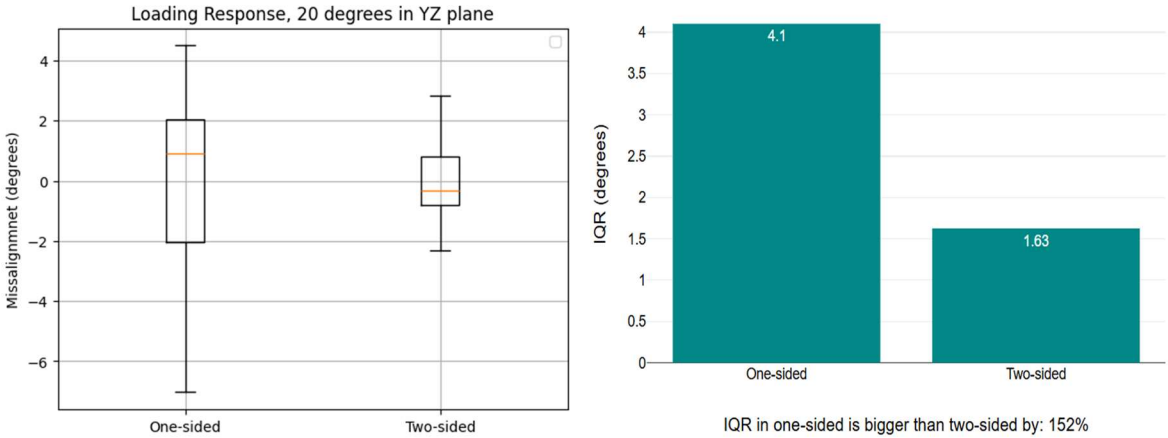


Figure 18– shows the misalignment in Loading Response.

The standard deviation is larger for one-sided orthosis (2.2255) than for two-sided orthosis, which has a standard deviation of 1.0149. The max/min for front data is a range of about 11.54 (-7.03 to 4.50) for one-sided orthosis, while two-sided orthosis has a range of about 5.13 (-2.30 to 2.82). The interquartile range for one-sided orthosis (4.102) is lower than the interquartile range for two-sided orthosis (1.626). The median for one-sided orthosis and two-sided orthosis is (0.9198 vs -0.3086). The spread is most extensive in the orthosis with one-sided support.

**Loading Response, 40 degrees in XY plane (One-sided vs two-sided)**

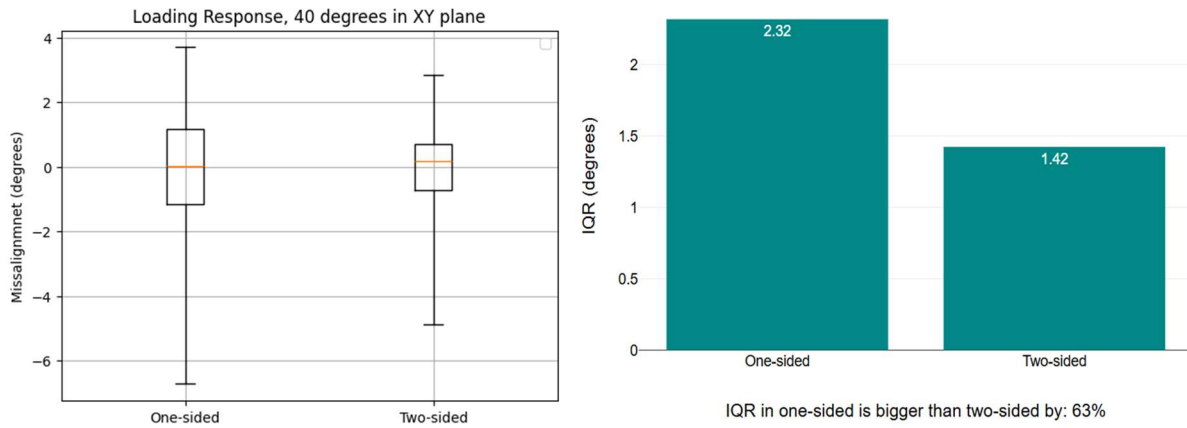


Figure 19 – shows the misalignment in Loading Response.

The standard deviation is larger for  $v$  (1.8054) than for the two-sided orthosis, which has a standard deviation of 1.0733. The max/min for front data is a range of about 10.42 (-6.72 to 3.70) for one-sided orthosis, while two-sided orthosis has a range of about 7.74 (-4.89 to 2.84). The interquartile range for one-sided orthosis (2.318) is lower than the interquartile range for two-sided orthosis (1.424). The median for one-sided orthosis vs two-sided orthosis is (0.0090 vs 0.1711). The spread is most extensive in the orthosis with one-sided support.

### Loading Response, 40 degrees in YZ plane (One-sided vs two-sided)

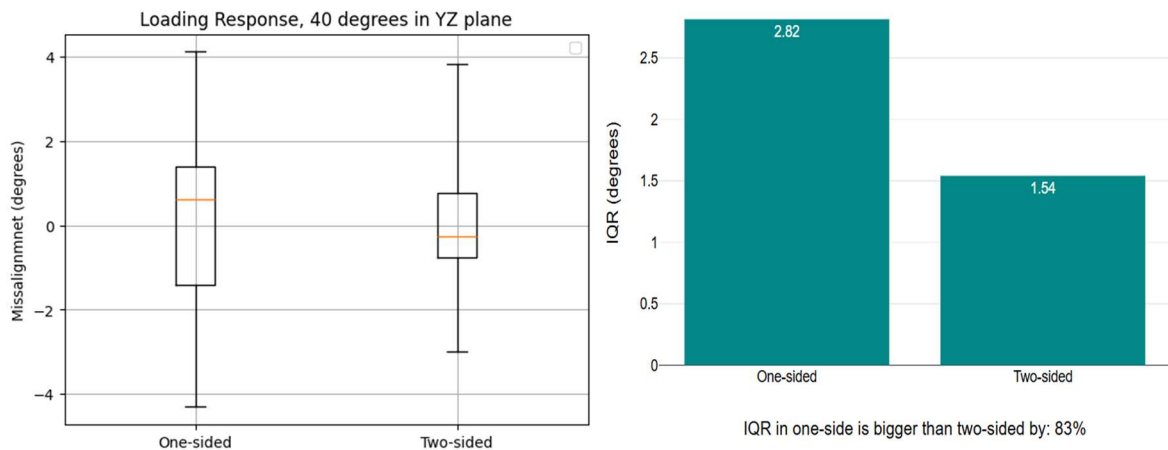


Figure 20 – shows the misalignment in Loading Response.

The standard deviation is larger for one-sided orthosis (1.7147) than for two-sided orthosis which has a standard deviation of 1.1819. The max/min for front data is a range of about 8.44 (-4.31 to 4.12) for one-sided orthosis, while two-sided orthosis has a range of about 6.84 (-3.00 to 3.84). The interquartile range for one-sided orthosis (2.815) is lower than the interquartile range for two-sided orthosis (1.541). The median for one-sided orthosis and two-sided orthosis is (0.6139 vs -0.2690). The spread is most extensive in the orthosis with one-sided support.

Mean values for "Loading Response" (lowest spread from each test plan)

$$\text{Mean Standard Deviation} = \frac{1.6679 + .0149 + 1.0733 + .1819}{4} = 1.2345$$

$$\text{Mean Interquartile Range} = \frac{1.759 + 1.626 + 1.424 + 1.541}{4} = 1.5875$$

### Mid-Stance, 20 degrees in XY plane (One-sided vs two-sided)

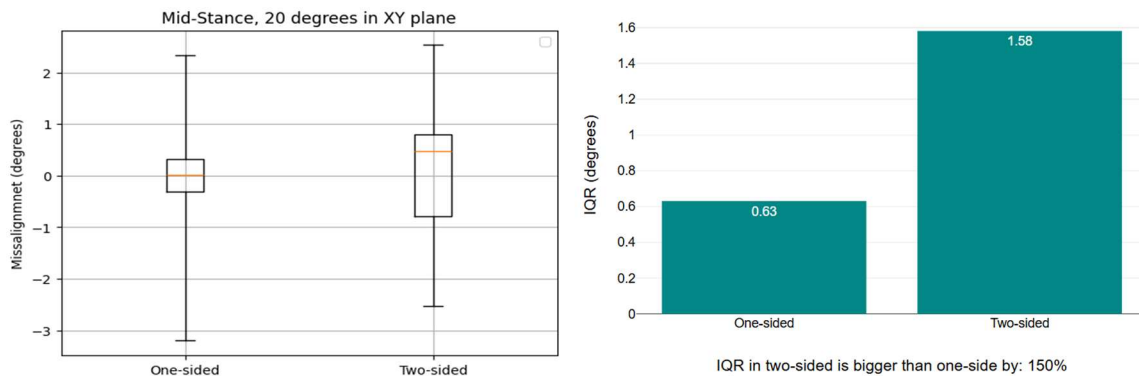


Figure 21 – shows the misalignment in Mid-Stance.

The standard deviation is lower for one-sided orthosis (0.55515) than for two-sided orthosis, which has a standard deviation of 0.99791. The max/min for mid data is a range of about 5.53 (-3.20 to 2.33) for one-sided orthosis, while two-sided orthosis has a range of about 5.06 (-2.52 to 2.53). The interquartile range for one-sided orthosis (0.6305) is shorter than the interquartile range for two-sided orthosis (1.581). The median for both is positive and close to zero (0.0194 vs 0.4736). The spread is most extensive in the orthosis with two-sided support.

### Mid-Stance, 20 degrees in YZ plane (One-sided vs two-sided)

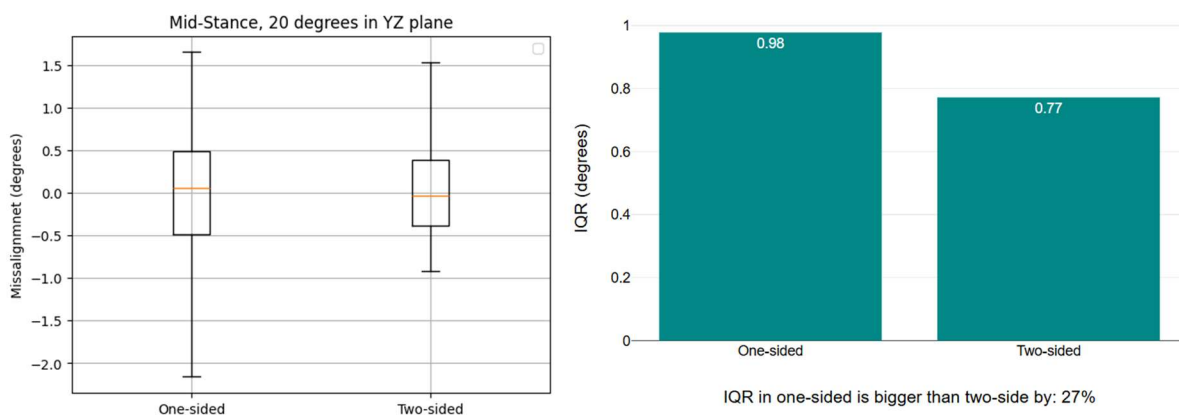


Figure 22 – shows the misalignment in Mid-Stance.

The standard deviation is larger for one-sided orthosis (0.69225) than for two-sided orthosis, which has a standard deviation of 0.52094. The max/min for mid data is a range of about 3.82 (-2.16 to 1.65) for one-sided orthosis, while two-sided orthosis has a range of about 2.46 (-0.92 to 1.53). The interquartile range for one-sided orthosis (0.978) is larger than the interquartile range for two-sided orthosis (0.772). The median for one-sided orthosis and two-sided orthosis is (0.0583 vs -0.0363). The spread is most extensive in the orthosis with one-sided support.

### Mid-Stance, 40 degrees in XY plane (One-sided vs two-sided)

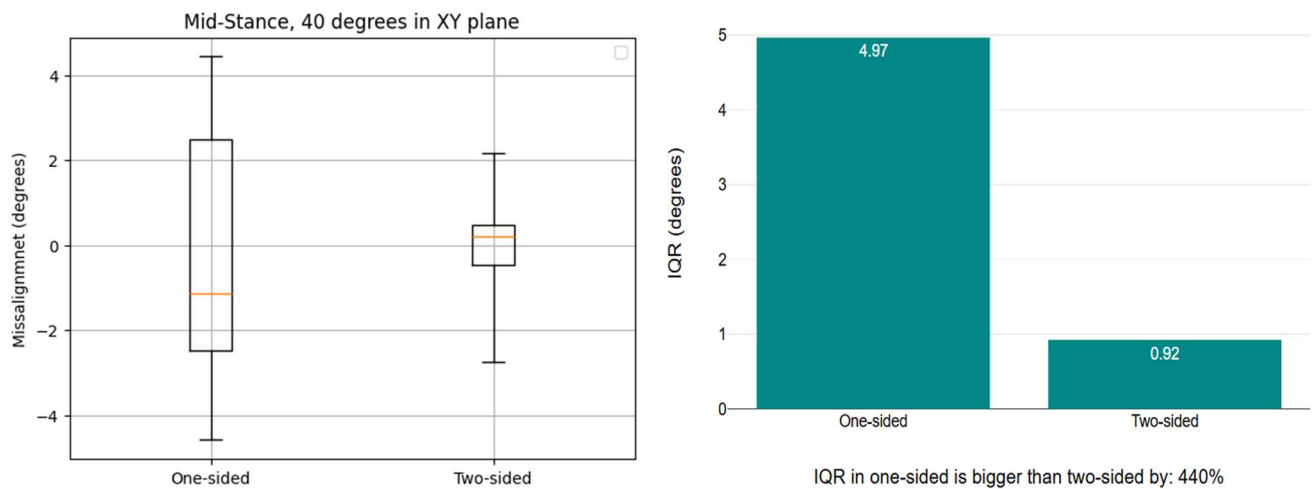


Figure 23 – shows the misalignment in Mid-Stance.

The standard deviation is larger for one-sided orthosis (2.5289) than for two-sided orthosis which has a standard deviation of 0.91957. The max/min for mid data is a range of about 9.02 (-4.58 to 4.43) for one-sided orthosis, while two-sided orthosis has a range of about 4.75 (-2.75 to 2.16). The interquartile range for one-sided orthosis (4.966) is larger than the interquartile range for two-sided orthosis (0.924). The median for both is (-1.1444 vs 0.1931). The spread is most extensive in the orthosis with one-sided support.

### Mid-Stance, 40 degrees in YZ plane (One-sided vs two-sided)

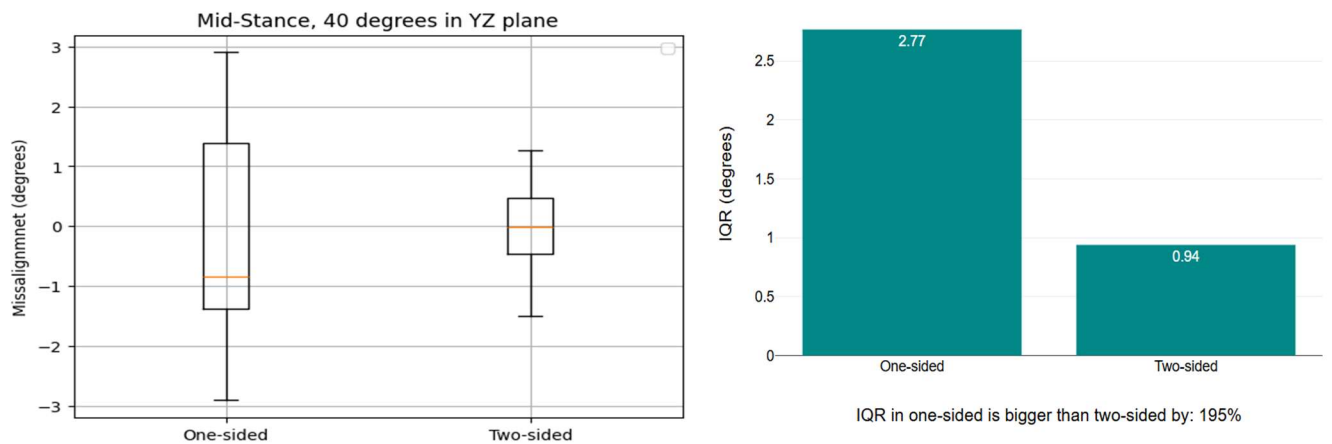


Figure 24 – shows the misalignment in Mid-Stance.

The standard deviation is larger for one-sided orthosis (1.4467) than for two-sided orthosis which has a standard deviation of 0.64418. The max/min for mid data is a range of about 5.8 (-2.908 to 2.9) for one-sided orthosis, while two-sided orthosis has a range of about 2.77 (-1.50 to 1.27). The interquartile range for one-sided orthosis (2.767) is larger than the interquartile range for two-sided orthosis (0.939). The median for one-sided orthosis and two-sided orthosis is (-0.8364 vs -0.0134). The spread is largest in the orthosis with one-sided support.

Mean values for "Mid-Stance" (lowest spread from each test plan)

$$\text{Mean Standard Deviation} = \frac{0.55515 + .52094 + .91957 + 0.64418}{4} = 0.6600$$

$$\text{Mean Interquartile Range} = \frac{0.6305 + 0.772 + 0.924 + 0.939}{4} = 0.8164$$

### Terminal Stance, 20 degrees in XY plane (One-sided vs two-sided)

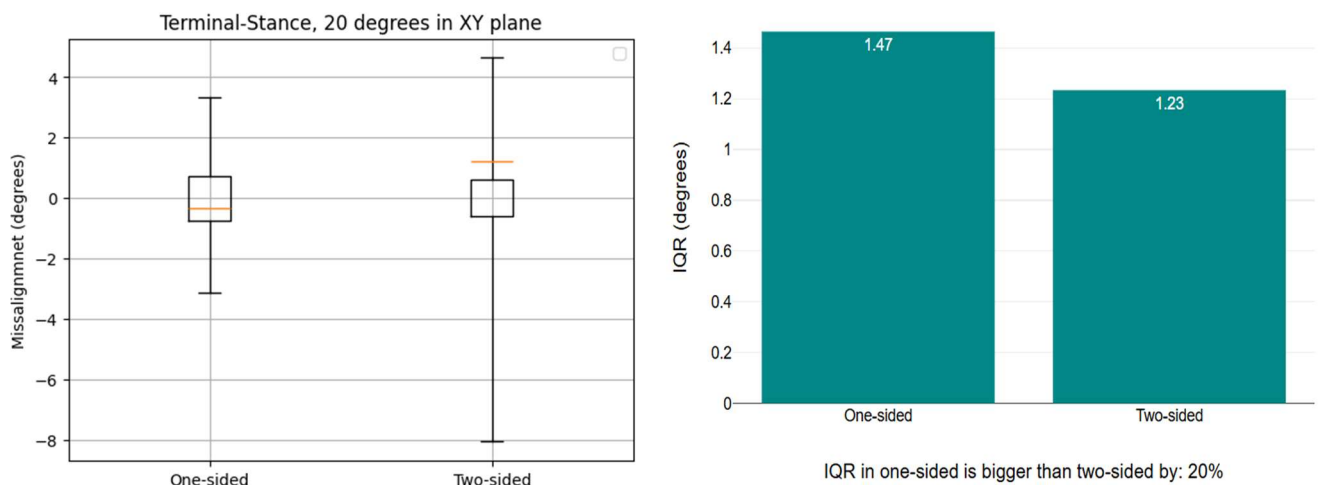


Figure 25 – shows the misalignment in Terminal Stance.

The standard deviation is larger for one-sided orthosis (1.245) than for two-sided orthosis which has a standard deviation of 1.0518. The max/min for mid data is a range of about 6.47 (-3.12 to 3.35) for one-sided orthosis, while two-sided orthosis has a range of about 12.72 (-8.07 to 4.64). The interquartile range for one-sided orthosis (1.465) is larger than the interquartile range for two-sided orthosis (1.234). The median for both (-0.3187 vs 1.234). The spread is largest in the orthosis with two-sided support.

### Terminal Stance, 20 degrees in YZ plane (One-sided vs two-sided)

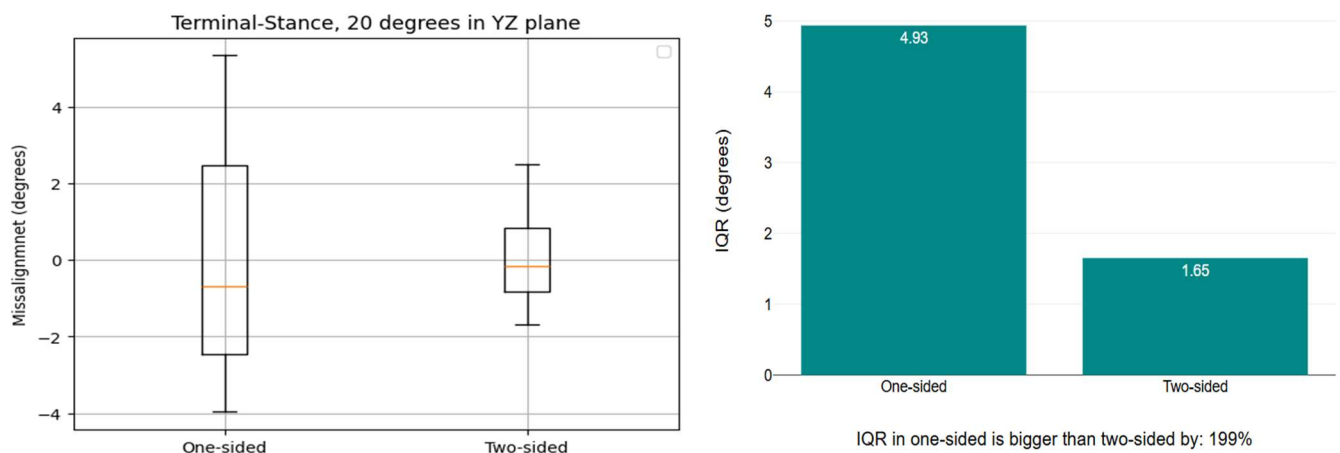


Figure 26 – shows the misalignment in Terminal Stance.

The standard deviation is larger for one-sided orthosis (1.4608) than for two-sided orthosis which has a standard deviation of 0.90224. The max/min for mid data is a range of about 9.31 (-3.97 to 5.34) for one-sided orthosis, while two-sided orthosis has a range of about 4.20 (-1.68 to 2.51). The interquartile range for one-sided orthosis (4.934) is larger than the interquartile range for two-sided orthosis (1.651). The median for one-sided orthosis and two-sided orthosis is (-0.6813 vs -0.1550). The spread is largest in the orthosis with one-sided support.

### Terminal Stance, 40 degrees in XY plane (One-sided vs two-sided)

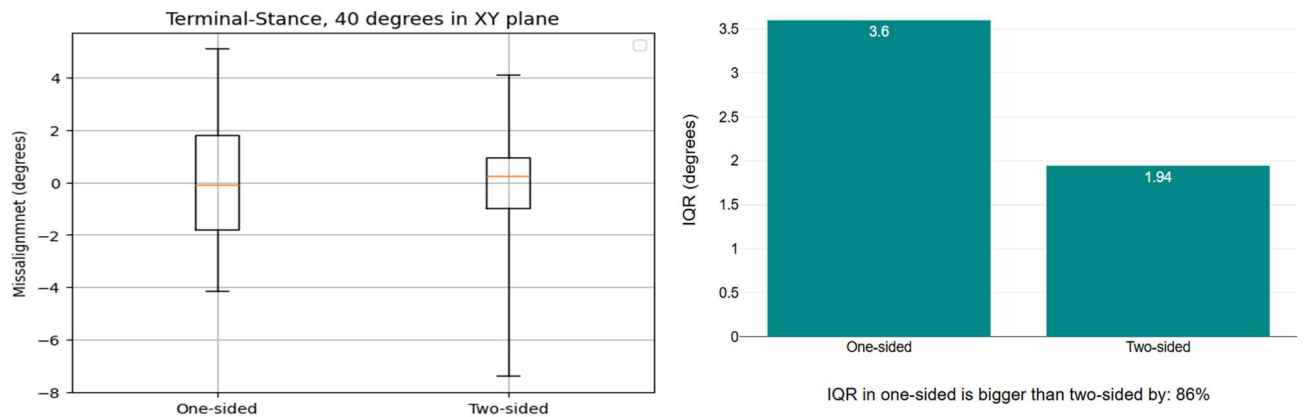


Figure 27 – shows the misalignment in Terminal Stance.

The standard deviation is larger for one-sided orthosis (2.0449) than for two-sided orthosis which has a standard deviation of 1.4502. The max/min for mid data is a range of about 9.25 (-4.15 to 5.10) for one-sided orthosis, while two-sided orthosis has a range of about 11.52 (-7.39 to 4.12). The interquartile range for one-sided orthosis (3.597) is larger than the interquartile range for two-sided orthosis (1.943). The median for both (-0.0844 vs 0.2610). The spread is most extensive in the orthosis with two-sided support, but has a smaller interquartile range (IQR).

### Terminal Stance, 40 degrees in YZ plane (One-sided vs two-sided)

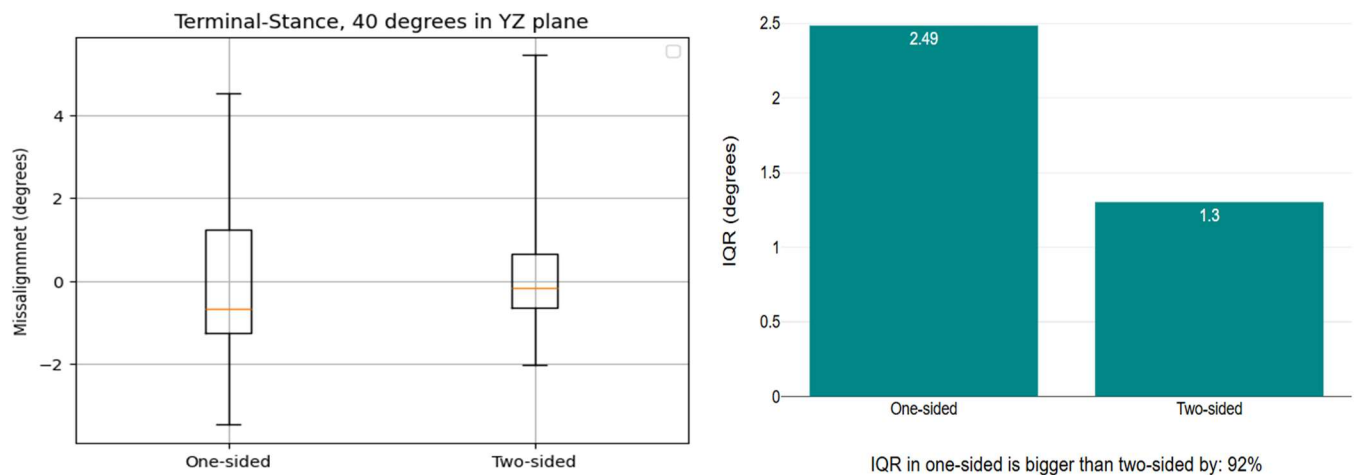


Figure 28 – shows the misalignment in Terminal Stance.

The standard deviation is larger for one-sided orthosis (1.739) than for two-sided orthosis which has a standard deviation of 0.89424. The max/min for mid data is a range of about 9.19 (-3.467 to 4.52) for one-sided orthosis, while two-sided orthosis has a range of about 7.47 (-2.02 to 5.44). The interquartile range for one-sided orthosis (2.486) is larger than the interquartile range for two-sided orthosis (1.303). The median for one-

sided orthosis and two-sided orthosis is (-0.6813 vs -0.1550). The spread is largest in the orthosis with one-sided support.

Mean values for **Terminal-Stance** (lowest spread from each test plan)

$$\text{Mean Standard Deviation} = \frac{1.0518+0.90224 + .4502+0.89424}{4} = 1.0746$$

$$\text{Mean Interquartile Range} = \frac{1.234+1.651+1.943+1.303}{4} = 1.5328$$

<b>kategori</b>	<b>Medel standardavvikelse (SD)</b>	<b>Medel interkvartilavstånd (IQR)</b>
<b>Mid-stance data</b>	0,6600	0,8164
<b>Terminal stance data</b>	1,0746	1,5328
<b>Loading response data</b>	1,2345	1,5875

Table 2: Compilation of average values for optimal spread per main category.

## 7. Conclusion and Discussion

When the purpose of an orthosis is to maximize stability and control to prevent unwanted movement like misalignment after surgery or injury, a large spread of measurement data (IQR) is considered undesirable. It refers to increased misalignment in the frontal plane and contradicts the primary function of the orthosis.

In this study, where the main focus was on the frontal plane (YZ plane), all six exercises in the frontal plane demonstrated that the bilateral (two-sided) knee orthosis provided less spread (IQR) compared to the unilateral (one-sided) knee orthosis. However, across the entire thesis, where we chose to examine the misalignment even in the transversal plane, the bilateral orthosis proved superior in 10 out of 12 cases. In the two cases where the unilateral orthosis appeared to be more advantageous, the outcome was observed in the transversal plane (XY plane). Additional studies are needed to reach a more conclusive understanding of the two instances where the unilateral orthosis outperformed the bilateral.

The results indicate that bilateral orthosis is generally superior and provides better stability and leads to better alignment, while the unilateral orthosis allows slightly more freedom of movement but also higher variation in knee motion. Overall, the bilateral design led to more controlled movement without restricting mobility, which can support safer and more efficient rehabilitation. We initially thought that almost all tests would show the two-sided support to be the best, but upon conducting the tests and analyzing the data, we found that the existing differences were not as significant as we had initially thought. On the other hand, small margins make a substantial difference in terms of stability and comfort.

Although the results cannot fully confirm that bilateral orthosis leads to less misalignment than the unilateral orthosis. The findings from this study indicate that bilateral support provides greater stability and safety in the frontal plane, which in turn could contribute to reduced misalignment. Nevertheless, further research is warranted to establish whether bilateral orthosis leads to less misalignment compared to unilateral orthosis. Including investigations of other exercises that may induce such deviations.

## Final Results

<b>Exercises</b>	<b>IQR</b>
<b>Loading Response, 20 degrees in XY plane (One-sided vs two-sided)</b>	IQR in two-sided is bigger than one-sided by: 33%
<b>Loading Response, 20 degrees in YZ plane (One-sided vs two-sided)</b>	IQR in one-sided is bigger than two-sided by: 152%
<b>Loading Response, 40 degrees in XY plane (One-sided vs two-sided)</b>	IQR in one-sided is bigger than two-sided by: 63%
<b>Loading Response, 40 degrees in YZ plane (One-sided vs two-sided)</b>	IQR in one-sided is bigger than two-sided by: 83%
<b>Mid-Stance, 20 degrees in XY plane (One-sided vs two-sided)</b>	IQR in two-sided is bigger than one-sided by: 150%
<b>Mid-Stance, 20 degrees in YZ plane (One-sided vs two-sided)</b>	IQR in one-sided is bigger than two-sided by: 27%
<b>Mid-Stance, 40 degrees in XY plane (One-sided vs two-sided)</b>	IQR in one-sided is bigger than two-sided by: 440%
<b>Mid-Stance, 40 degrees in YZ plane (One-sided vs two-sided)</b>	IQR in one-sided is bigger than two-sided by: 195%
<b>Terminal Stance, 20 degrees in XY plane (One-sided vs two-sided)</b>	IQR in one-sided is bigger than two-sided by: 20%
<b>Terminal Stance, 20 degrees in YZ plane (One-sided vs two-sided)</b>	IQR in one-sided is bigger than two-sided by: 199%
<b>Terminal Stance, 40 degrees in XY plane (One-sided vs two-sided)</b>	IQR in one-sided is bigger than two-sided by: 86%
<b>Terminal Stance, 40 degrees in YZ plane (One-sided vs two-sided)</b>	IQR in one-sided is bigger than two-sided by: 92%

Table 3: IQR Summary for All Exercises

Even though we are satisfied with the results, given the limited resources and knowledge within the field during the time available, there are certain aspects we could have approached differently. Future work should try different methods for calculating the misalignment. A method that also captures knee rotation/twisting. Other areas that should be focused on are filtering and dividing the data into intervals, so that you only get the measured data of the tests and no other data. Additionally, adding a small Raspberry Pi can help calculate important data and ensure that the test is done correctly and with the correct values. However, this result is extremely important for optimizing knee rehabilitation and improving patients' functional outcomes.

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