Evidence based data processing for on-field agility T-test for ACL patients

Bachelor Thesis

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Contents

1 Abstract

ACL patients who have undergone ACL-reconstruction, will perform tests in the end of their rehabilitation to assess their readiness to return to sport. Currently, most tests are performed in a lab in a controlled environment. To reduce the gap between the controlled lab environment and the outside playing field, the agility T-test will be researched. A literature study was carried out to find parameters which can be measured during an agility T-test and can indicate a difference between the affected and non-affected side of an ACL patient, and thus say something about the readiness to return-to-sport. From the literature study, it is found that the hop tests and strength tests are the most common tests, with respectively the distance and power as main parameters. The distance is a parameter that can also be measured during a T-test with the used IMUs (Movella Xsens Awinda), which hasn't been done yet.

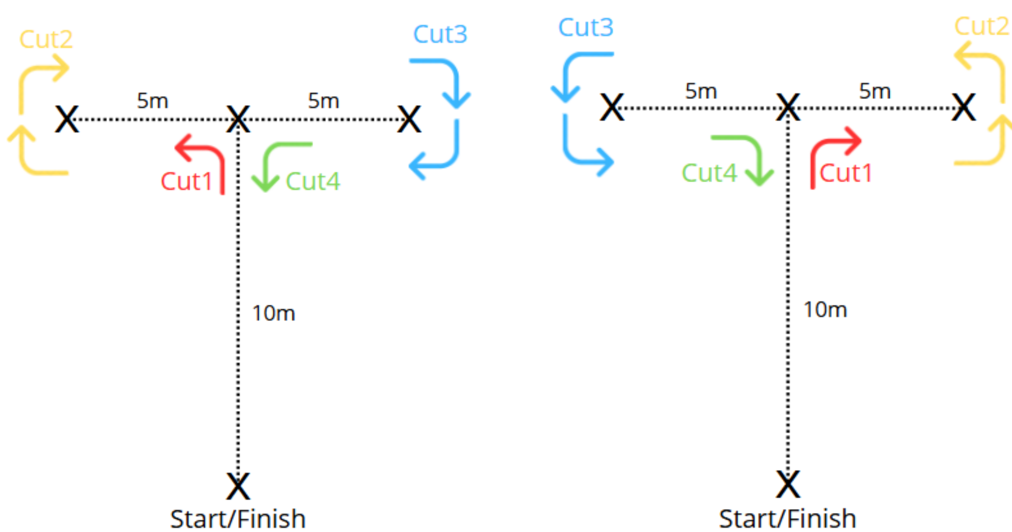
For the T-test, an experiment was conducted with the use of the Movella Xsens Awinda sensors. A subject had to run the T-test, and thus make 4 cuts in total (2 times 90°, 2 times 180°). With the use of a videocamera, the foot contacts (the moment the subject hits/releases the ground with his foot) were located. This was compared with the foot contacts found by the Xsens sensors, and thus the accuracy of the sensors could be validated. This resulted in an offset of 1 to 3 milliseconds, which is negligible for this research.

Next, The sharpness of the 90°cuts and 180°cuts is researched, which relates to the covered distance during a cut. For the 90°cuts, a circle is fitted to the cut. The results show that when a cut is done with the affected side as cutting leg, the average radius of the circle is smaller than when the subject cuts with the non-affected leg, which means a sharper cut. For the 180°cuts, the average distance between the incoming and outgoing trajectory is calculated. Here also the results show the average distance with the affected side as cutting leg is smaller, and thus a lower covered distance during the cut. It resulted in a small visible trend, where the cuts performed with the affected side as cutting leg had a sharper cut than the cuts done with the non-affected side.

2 Introduction

Patients after receiving an anterior cruciate ligament (ACL) reconstruction, go through a 3 phase rehabilitation process [1]. In the third phase where they are training to return to play, agility tests can be performed to assess their readiness to resume participation in team sports [1]. Balance, coördination, power and speed have been defined as the components of agility [2]. An agility test assesses these components by having a patient perform directional changes at speed [3].

There are multiple agility tests, like the Y-shaped test, T-test or side step test [2, 3]. Currently the performance of these tests are judged qualitatively. A research team of UT, Pro-F, Zuyd Hogeschool and OCON are working on quantitative assessment of the agility tests to create a test battery which reduces the gap from rehabilitation to return-to-competition. The T-test will be used in this research. During an agility T-test, a patient has to complete a running course in the shape of an 'T' (Fig. 1) as quick as possible. The patient will start at the bottom of the 'T', and run towards the first cutting point (cut1). Here the patient has to touch the ground (marked with an 'X' in Figure 1) with their hand. Depending on the direction of the test, the patient makes a 90°turn left or right. The patient then runs in a forward motion to the second cutting point, which is a 180°cut. After the first 180°cut (cut2), the patient runs to the other side to make another 180°cut (cut3), before returning to the middle of the 'T' and making the last 90°cut (cut4). At all cutting points, the patient has to touch the ground with their hand. The finish is at the same position as the starting point.

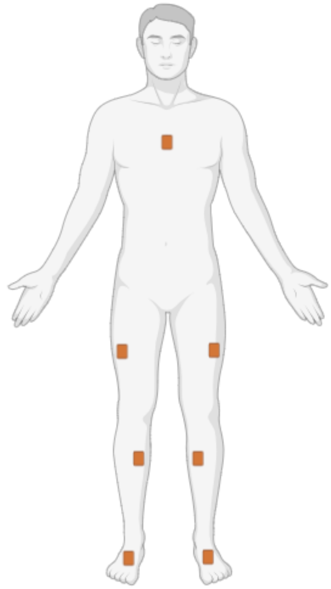


(a) T-test to the left

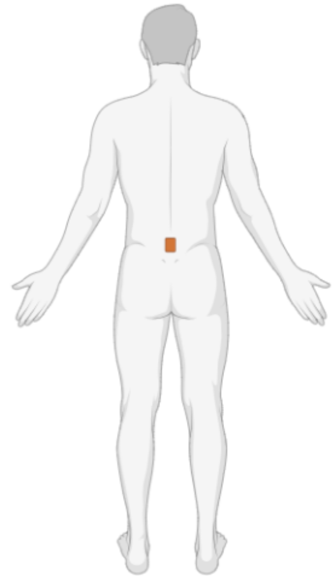
(b) T-test to the right

Figure 1: T-tests with the corresponding cuts as used with the data processing

The patient will be equipped with an Movella Xsens Awinda system. Multiple sensors will be placed on the patients legs, pelvis and sternum (Fig. 2). These sensors have the ability to track motion related parameters like joint angles, position and speed [4].



(a) Anterior view



(b) Posterior view

Figure 2: Xsens Awinda sensor placement on the body of the patients. Sensors are placed on the feet, lower legs, upper legs, pelvis and sternum

The T-test is done to measure multiple parameters. Some parameters are already commonly measured, like the completion time of the T-test which expresses the agility performance of the patient [3], and the joint angles [5] as was found by the research in the MSc thesis of Tjeerdtje van Gastel [6]. With the help of a literature study, more motion related parameters will be sought which are proven to indicate a difference between the affected and non-affected knee in ACL patients. The research question 'Which parameters measured during any agility test offer discrimination between healthy and affected side during the rehabilitation of patients with anterior cruciate ligament reconstruction?' will give answers to this. This will be the first part of this research.

For the second part of this research, a data algorithm is developed to automatically process the data. To do this, the exact cutting moments need to be found to be able to determine the length of a cut. With the cutting lengths known, parameters found in the literature study can be checked and quantified to see if they indicate a difference in the affected and non-affected knee of the patients.

3 Literature Research

A research strategy is worked out in detail, to be able to search more specifically for relevant articles.

3.1 Definitions and Abbreviations

The definitions and abbreviations are shown in Table 1 and Table 2. This will make the literature more readable and better to understand.

Table 1: Relevant definitions and their meaning

Definition	Meaning
Knee valgus	When the bone at the knee joint is angled out and away from the body's mid-line, which results in a lack of dynamic stability [7]
Anterior cruciate ligament reconstruction	The reconstruction of a ruptured acl with the use of an allo- or autograft [8]

Table 2: Relevant Abbreviations and their definition

Abbreviation	Definition
ACL	Anterior Cruciate Ligament
ACLR	Anterior Cruciate Ligament Reconstruction
RTS	Return-to-sport
ACL-RSI	Anterior Cruciate Ligament Return to Sport after Injury

3.2 Research Question

A research question is defined to which an answer is sought in the literature. From this question the search string will be formulated. The research question is:

'Which parameters measured during any agility test offer discrimination between healthy and affected side during the rehabilitation of patients with anterior cruciate ligament reconstruction?'

3.3 Search Strategy

To formulate a search string, synonyms of the relevant words in the research question are needed (Table 3). This will make sure to find all the articles which might be relevant, and not exclude any due to different synonyms used.

Table 3: Relevant synonyms that can be used in the search string

Term from research question	Parameters	Agility Test	Return-to-sport	Anterior Cruciate Ligament Reconstruction	
Synonyms	Metric	T-test	Return-to-participation	ACL rupture	Distance
	Variable	Change of direction test	Return-to-play	ACL reconstruction	Time
	Criterion	Hop test	Sports participation	ACL surgery	Joint angle
		Dynamic movement test	Return-to-training	ACL patients	Kinematics
		Functional performance test	Return-to-competition	ACL injury	Strength
					Valgus
					Agility
					Limb symmetry

The finalized search string used for the literature research in PubMed:

(Agility test[tiab] OR T-test[tiab] OR change of direction test[tiab] OR hop test[tiab] OR dynamic movement test[tiab] OR functional performance test[tiab]) AND (anterior cruciate ligament[tiab] OR acl[tiab] OR acl reconstruc* [tiab] OR acl surgery [tiab] OR acl injur* [tiab] OR acl patient[tiab] OR acl ruptu*[tiab]) AND (paramet* [tiab] OR metric*[tiab] OR variabl* [tiab] OR criter*[tiab] OR time[tiab] OR joint angle[tiab] OR kinematic*[tiab] OR strength[tiab] OR valgus[tiab] OR agil*[tiab] OR limb symmet*[tiab] OR distance[tiab] OR knee function*[tiab])

Inclusion criteria:

- Full text available
- Text in English
- Tests performed with humans
- Article published between 2014 and 2024
- Multiple parameters used
- Goal of test is to return-to-sport

The finalized search string and inclusion criteria have resulted in 269 articles. The articles are sorted on best match. The first 50 articles were scanned on their title and abstract. The articles were sorted in 3 groups: Relevant, Doubt and Not relevant. An article was placed in the group Relevant if it had information about tests used on ACL patients that want to return-to-sport. It should also include the parameters that are measured. The articles from the group Relevant are used for the literature review.

The information that needs to be extracted from the relevant articles is:

- Which parameters are used during different tests
- How parameters are measured
- If parameters offer discrimination between non-affected and affected side

The information extracted from the articles will be sorted in a table to create an overview.

3.4 Results

From the 50 articles that are screened on title and abstract, 9 articles were placed in the group Relevant based on the criteria mentioned above. The 9 relevant articles were more thoroughly screened to find relevant information. The results can be found in Table 5 and are summarised below.

The most common test is the hop test, as 5 out of 9 studies used the hop test (Table 4) [9–13]. Different variations of the hop test exists, namely the single leg hop , crossover hop, triple hop and 6 meter timed hop tests [9]. The first three hop tests use distance (in meters) as the parameter. The 6 meter timed hop test uses, as the name suggests, time (in seconds) and distance as a parameter [9]. In one study, the acceleration of the foot was also measured using wearable magneto-inertio measurement units (MIMU's) to identify the take-off and landing time [13]. The hop tests are performed with the affected and non-affected leg. This gives the opportunity to calculate the limb symmetry index (LSI). If a patient has a limb symmetry of 90% or higher, the patient complies with the return-to-sport criteria [9–11].

Table 4: Overview of the number of times a test is used in the 9 relevant articles

test	Number of times used
Hop test	5
Strength test	5
Question form	3
Vertical jump	3
Agility test	1
Gait phase	1

Strength test are other commonly used tests to indicate if a patient is ready to return-to-sport, as they also appear in 5 studies (Table 4) [9–12, 14]. With a dynamometer the strength in the quadriceps and hamstrings are measured when the patient performs knee extension and flexion movements [12, 14]. The Peak Torque to Bodyweight ratio (PT/BW) and the Hamstring to Quadricep ratio (H/Q) are derived from the measurements [10,14]. For this test also a minimum of 90% limb symmetry is needed to be able to return-to-sport safely. [9–11]

Change-of-direction tests and gait phase testing uses the completion time (in seconds) and the joint angles (in degrees) as useful parameters [5,10]. Most of the parameters measured during the hop tests and strength test, cannot be tested with the change-of-direction test and the available materials.

However, a parameter that is not tested yet in change-of-direction tests, but is used in hop tests, is the distance [9–13]. The distance traveled by the patient during the cut-moments, could be of interest for part 2 of this research.

Table 5: Overview of relevant information from literature research

Used tests	Measured parameters	Units	Measure method	Cleared for RTS	Test details	First author	Year
Hop tests	Distance	m		>90% limb symmetry	Single, crossover, triple, 6-m timed	Arundale	2017
Hop tests	Distance	m		>90% limb symmetry		Kyritsis	2016
Hop tests	Distance	m		>90% limb symmetry		Losciale	2022
Hop tests	Distance	m				van Melick	2022
Hop test	Distance	m				Baldazzi	2022
	Acceleration	m/s^2	MIMU			Baldazzi	2022
Quadricep strength test	Maximal volitional isometric contractions	Nm	Dynamometer	>90% limb symmetry	Seated on machine, hips and knees 90°	Arundale	2017
Knee muscle testing	PT/BW		Dynamometer	Knee extention and flexion strength	Velocity 60°/sec and 180°/sec, seated position	Cvjetkovic	2015
	Average power		Dynamometer	Knee extention and flexion strength	Velocity 60°/sec and 180°/sec, seated position	Cvjetkovic	2015
	H/Q ratio		Dynamometer	Knee extention and flexion strength	Velocity 60°/sec and 180°/sec, seated position	Cvjetkovic	2015
Concenctric isokinetic test	Peak torque		Dynamometer	Quadricep deficit <10% at 60°/sec	Velocity 60°/sec and 180°/sec and 300°/sec, seated position	Kyritsis	2016

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Table 5 – continued from previous page

Used tests	Measured parameters	Units	Measure method	Cleared for RTS	Test details	First author	Year
	PT/BW		Dynamometer	Quadricep deficit <10% at 60°/sec	Velocity 60°/sec and 180°/sec and 300°/sec, seated position	Kyritsis	2016
	Work fatique		Dynamometer	Quadricep deficit <10% at 60°/sec	Velocity 60°/sec and 180°/sec and 300°/sec, seated position	Kyritsis	2016
	Average power	W	Dynamometer	Quadricep deficit <10% at 60°/sec	Velocity 60°/sec and 180°/sec and 300°/sec, seated position	Kyritsis	2016
	H/Q ratio		Dynamometer	Quadricep deficit <10% at 60°/sec	Velocity 60°/sec and 180°/sec and 300°/sec, seated position	Kyritsis	2016
Quadricep strength test	Average peak torque		Dynamometer	>90% limb symmetry		Losciale	2022
Isometric knee extensor/flexor strength	Peak torque	Kg	Dynamometer			van Melick	2022
Eccentric knee flexor strength	Peak torque	Kg	Dynamometer			van Melick	2022
IKDC subjective knee form	Knee symptoms		Scale from 0% to 100%	Score above 15% of age- and sex matched healthy individuals		Arundale	2017

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Table 5 – continued from previous page

Used tests	Measured parameters	Units	Measure method	Cleared for RTS	Test details	First author	Year
	Knee function		Scale from 0% to 100%	Score above 15% of age- and sex matched healthy individuals		Arundale	2017
	Sports activity		Scale from 0% to 100%	Score above 15% of age- and sex matched healthy individuals		Arundale	2017
KOOS	Degree of difficulty with tasks		Scale from 0% to 100%			Arundale	2017
IKDC subjective knee form	Knee symptoms		Scale from 0% to 100%	>90		Losciale	2022
	Knee function		Scale from 0% to 100%			Losciale	2022
	Sports activity		Scale from 0% to 100%			Losciale	2022
Drop vertical jump	Knee flexion angle	°	3D motion analyis with cameras		Drop from box, land and immediately maximal effort jump	Losciale	2022
	GRF	N/kg	Force plates			Losciale	2022
	Knee RoM	°				Rambaud	2018
	Quadricep	Hamstring strength				Rambaud	2018
Vertical jump test	Height	m			Jump with one leg from ground position	van Melick	2022

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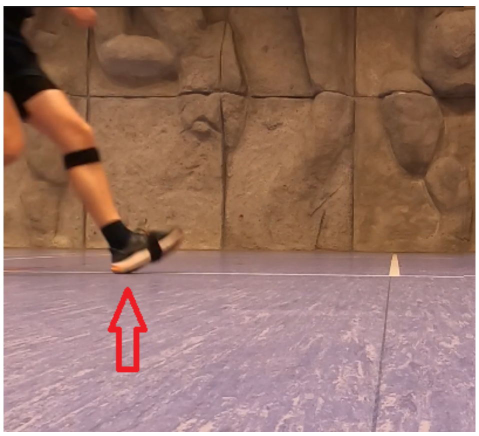
Table 5 – continued from previous page

Used tests	Measured parameters	Units	Measure method	Cleared for RTS	Test details	First author	Year
Vertical jump test	GRF	N	Force plates			Baldazzi	2022
Gait phases	Joint angles of hip, knee and ankle		2D video			Bari	2022
	Cadence	steps/min	2D video			Bari	2022
	Gait velocity	m/s	2D video			Bari	2022
	Step length	m	2D video			Bari	2022
	Stride length	m	2D video			Bari	2022
Agility T-test	Time	s		<11 s	Using side-steps	Kyritsis	2016
Single leg squat	Angular displacement	°	MIMU			Baldazzi	2022

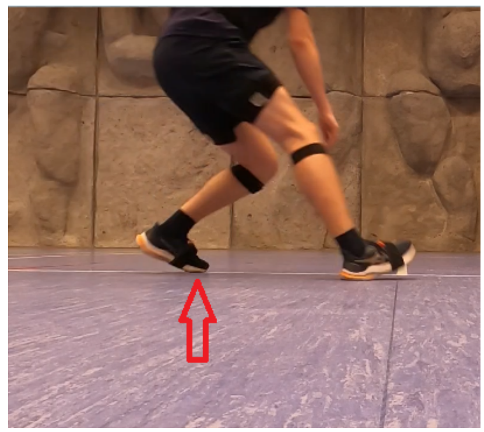
4 Methods

4.1 Experimental set-up

For this research, it is important to find the exact moments of the begin and the end of the cutting moment. The MVN Analyze software of the Xsens sensors can automatically find the moments when there is a heel-strike (the first contact of the foot with the ground during a step (Fig. 3(a))) and a toe-off (the last contact of the foot with the ground during a step (Fig. 3(b))). However, the accuracy of this automatic function to find these points was unknown. Therefore, an experiment was conducted where the accuracy of the software was validated. This was done by the use of video-camera's.



(a) Heel-strike of left foot

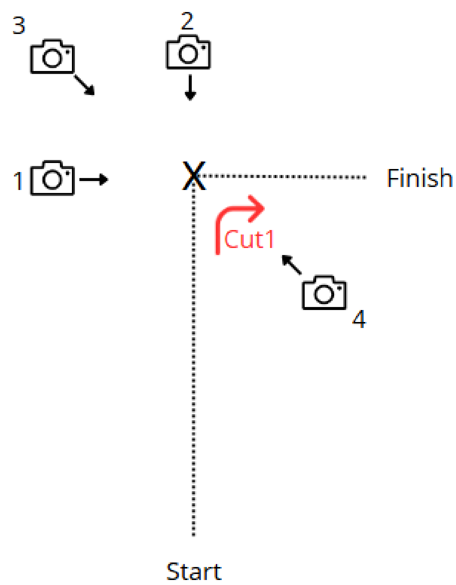


(b) Toe-off of left foot

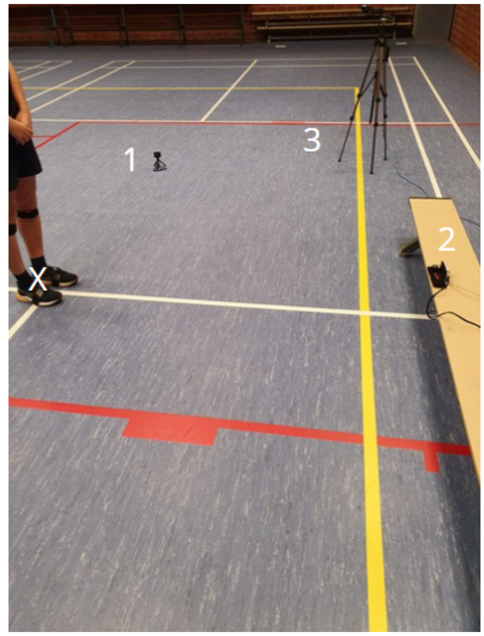
Figure 3: Heel-strike and toe-off of left foot during cutting moment

In the setup (Fig. 4(a)), 4 different camera's were used. This was done to find the camera with the highest framerate and the easiest to synchronize with the data. The 4 camera's were a GoPro Hero 8 Black (120 fps), a webcam (24 fps), the Allied Vision Prosilica GS650C Medical (60 fps) and the camera from a mobile phone (30 fps). There were also 4 different camera positions tested (Fig. 4).

The Allied Vision Prosilica GS650C medical, which was provided by the Xsens set, was not suitable for this experiment. While the synchronization would be perfect due to the connection of a network cable between the camera and laptop, the video footage appeared to flicker randomly throughout the video. It was therefore impossible to find the correct frames. For the other camera's, it was not possible to automatically synchronize the footage to the data. Therefore, the only relevant difference was the framerate. The GoPro Hera 8 Black had the highest possible framerate of 120 fps. The GoPro was chosen as the best suitable camera for this experiment.



(a) Schematic drawing of the camera set-up



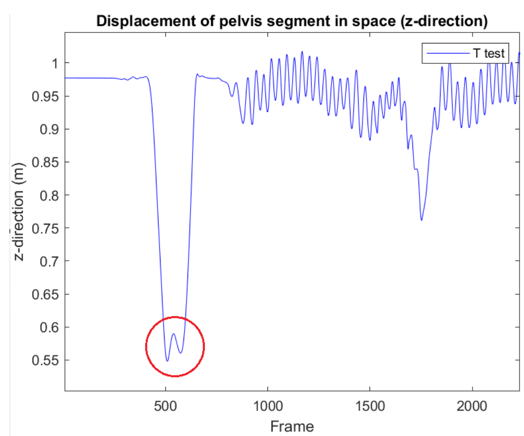
(b) Camera set-up during testing. The subject is standing on the spot marked with 'X' in Figure 4(a). Camera position 4 is out of thispicture.

Figure 4: Overview of camera set-up

Camera position 1 (Fig. 4(a)) appeared to be the best position. It clearly records the heel-strike and toe-off of the best. The camera was positioned at a distance of 2 meters from the cutting position, and the lens was placed 15 cm above the ground. The use of a second camera at position 2 did not provide any extra insights, and was thus not needed.

To be able to later synchronize the video footage with the data from Xsens, the subject performed a squatting movement in front of the camera. This is because a squat can clearly be seen in the plot of the pelvis displacement in the z-direction (Fig. 5).

(a) Squatting movement performed by the subject



(b) Displacement of pelvis segment in z-direction, with the lowest position of the squatting movement circled in red

Figure 5: Squatting movement performed by the subject on the left, with corresponding data circled in red on the right

The first 90°turn (cut1) from the T-test was used for this experiment (Fig. 4(a)). The subject, who was equipped with the Xsens Awinda sensors on the lower body, pelvis and sternum (Fig. 2), had to run forward towards the turning point, make a 90 degree turn and run in a forward motion away from the turning point. The subject had to touch the ground at the turning point (marked with 'X' in Figure 4(a)) with their hand while turning. 8 measurements were conducted (Table 6). A measurement consisted of the subject performing a squat, and afterwards running the first part of the T-test (only cut 1).

Table 6: Overview of the direction and surface material of the measurements

Measurement	Turning direction	Surface material
1	Right	Grass
2	Right	Grass
3	Left	Grass
4	Left	Grass
5	Right	Athletics track
6	Right	Athletics track
7	Left	Athletics track
8	Left	Athletics track

For the measurements with the patients, the full T-test was performed (Fig. 1). These measurements will provide the data to be used for the research of the different parameters found in the literature review. At the start, time gates were placed to keep track of the completion time of the test. The patient was equiped with the Xsens sensors, and had to follow the calibration procedure of the system. The patients completed 4 measurements; two to the left and two to the right. In between the tests the patient gets 2 minutes of rest. The 90°cuts are respectively cut1 and cut4, and the 180°cuts are respectively cut2 and cut3 in Figure 1. The goal was to complete the test as quick as possible. At every cutting moment, they had to touch the ground with their hand, which was placed at the X-marks (Fig. 1).

4.2 Data processing

The goal of the data processing is to find the accuracy of the Xsens sensors by comparing the frames of the video camera and the frames of the Xsens data.

For the processing of the video footage, the software editor Davinci Resolve [15] is used. Here, the footage is imported at 60 fps (the highest possible).

First, the footage is being cut at the moment where the subject hits the lowest position of the squat for the first time with their pelvis (Fig. 5). This now corresponds with the first frame of the video. Secondly, the video frames with the begin and end of the cut need to be found. This corresponds respectively with the heel strike of the cutting leg, and the toe-off of the cutting leg (Fig. 6). This is done manually by going through the video frames. The correct video frames are saved in a table and used later in the Matlab script (see Appendix A.1 and A.2). The edited video is exported in 60 fps.

(a) Begin of the cut

(b) End of the cut

Figure 6: Video frames of the begin and end of the cut

Next, the data from the Xsens and the edited video can be imported in Matlab. The corresponding frames of the begin and end of the cut can be filled in in the Matlab script (Fig. 6). The script will calculate the corresponding frames of the Xsens, because the video is in 60 fps, and the data from Xsens is in 100 fps. Next, the synchronization of the video footage and the Xsens data needs to be done. This is done by selecting the lowest point in the plot of the pelvis displacement in z-direction (Fig. 5(b)). The corresponding x-value of the selected point is the Xsens frame that is needed in the matlab script. The video footage and Xsens data is now synchronized, because the begin and end of the cut as found by the video footage is plotted with the displacement of the pelvis segment in space as found by the Xsens data (Fig. 7).

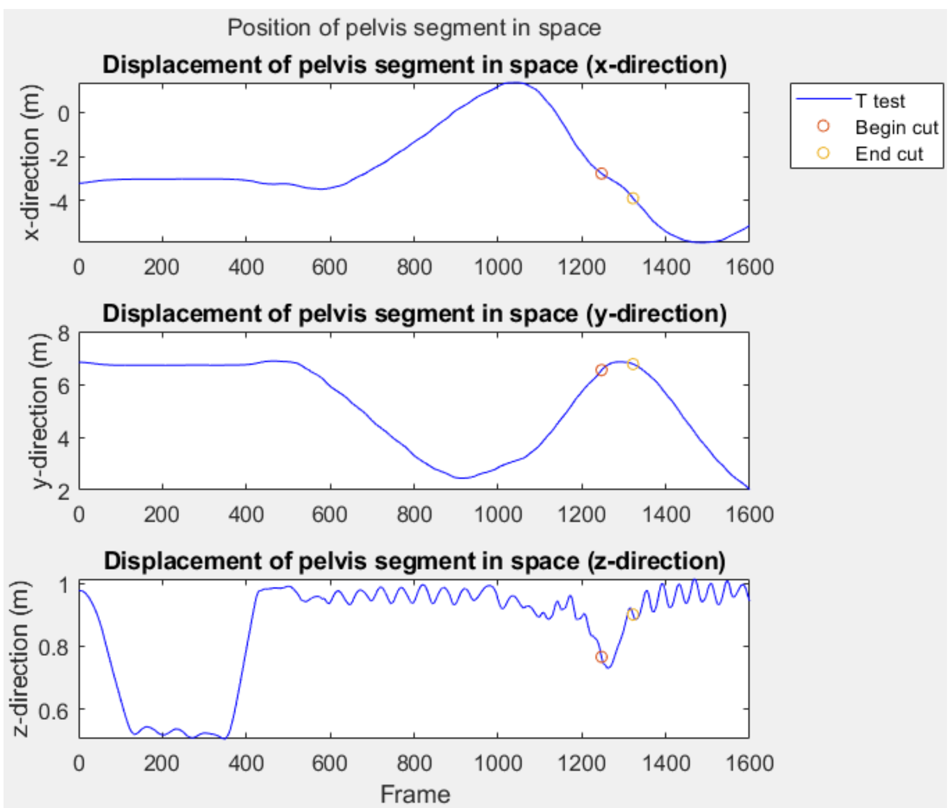


Figure 7: Displacement of pelvis segment in space, with the begin and end of the cut plotted as markers.

Finally, the cutting moments as found by the video footage and as found by the Xsens data is being compared. The pelvis displacement in z-direction is plotted, with the initial contact (heel strike) and final contact plotted as markers in the graph (Fig. 8). X=1 Corresponds with the video frame of the initial contact of the foot, as found with the footage. The initial contact as found by the Xsens data is plotted as a marker. Now, the offset in frames for the initial contacts can be found and compared by taking the difference in x-values. The same can be done for the toe-off.

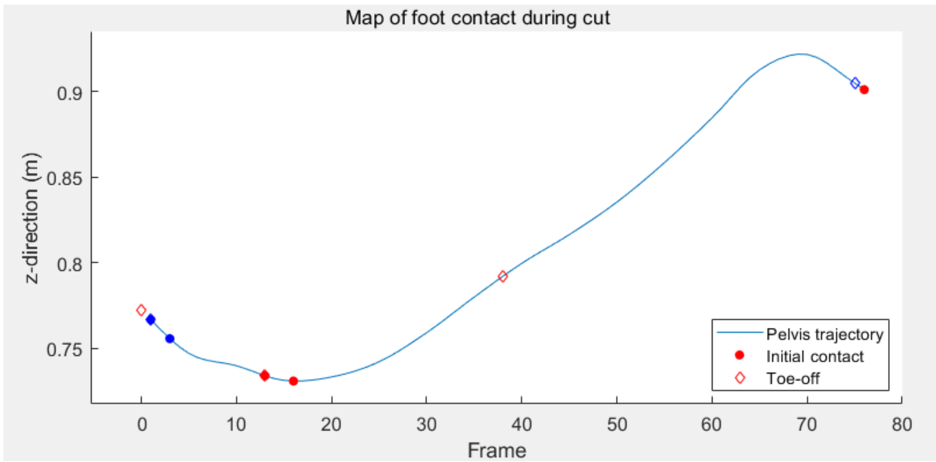


Figure 8: Foot contacts plotted in the graph with pelvis displacement in z-direction. The blue markers correspond with the cutting leg. In this figure, the initial contact has an offset of +2 frames, and the toe-off has an offset of -1 frame. This pelvis trajectory corresponds with the trajectory of Figure 7 in z-direction between the makers.

4.3 Data Analysis

The goal of the data analysis is to find out how wide or how sharp a patient takes the cut. The literature study has shown that the distance a patient covers could indicate a difference between the affected and non-affected side. A different analysis method is used for the 90°cuts and the 180°cuts.

For the 90°cuts (cut1 and cut4 in Fig. 1), a circle is fitted which fits the datapoints the best during the cut (Fig. 10). The radius of the circle (Rcirc) gives an indication of the sharpness of the cut. If the radius is smaller, the cut is taken sharper and the covered distance is smaller. As mentioned before, the covered distance could be an parameter of interest. To determine the length of the cut (Lcut), the middle of the cut is located. This is done by plotting the pelvis trajectory in the z-direction. From this, the 4 points with the lowest y-value are selected. These points correspond with the drop of the pelvis height, which is a manoeuvre done during a cut. This can be seen in Figure 9, where the color of the cutting points correspond with the cuts as seen in Figure 1.

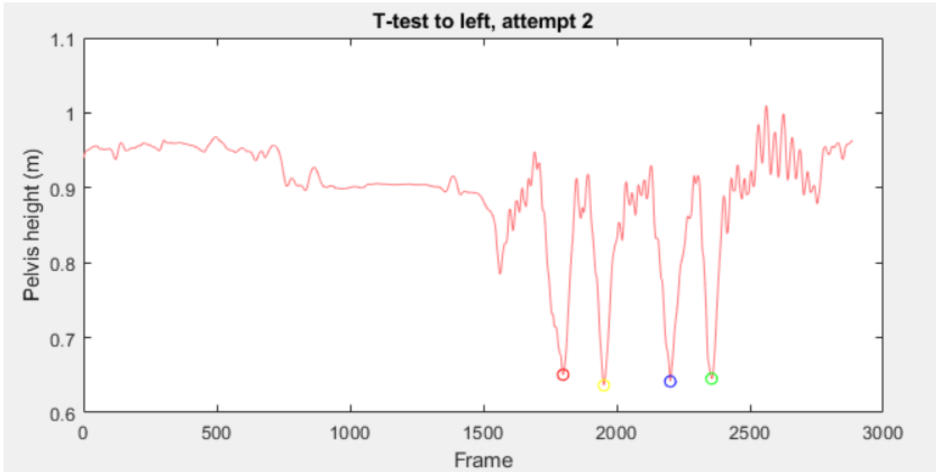


Figure 9: Displacement of pelvis in z-direction, with the cuts plotted as markers. The colors of the cuts correspond with the cuts in Figure 1.

The full cutting manoeuvre is calculated by taking the middle of the cut, and taking 30 frames before and after this moment. It now thus consists of 61 frames.

To calculate the radius and origin of the circle, the general equation for a circle is first used:

$$(x - xo)^2 + (y - yo)^2 = R^2$$

Where xo and yo are the origin of the circle, and R is the radius. By rewriting this formula it can be put into matrix form:

$$x^2 - 2 * x * xo + xo^2 + y^2 - 2 * y * yo + yo^2 = R^2$$

$$\begin{pmatrix} -2x & -2y & 1 \end{pmatrix} \times \begin{pmatrix} xo \\ yo \\ -R^2 + xo^2 + yo^2 \end{pmatrix} = - \begin{pmatrix} x^2 & y^2 \end{pmatrix}$$

By solving this in the least squares way, it will result in the following matlab code:

```
A = [-2*x -2*y ones(length(x),1)];
x = A\-(x.^2+y.^2);
xo=x(1);
yo=x(2);
R = sqrt(  xo.^2 + yo.^2  - x(3));
```

The full script can be found in Appendix A.1 and A.3.

The input is the x- and y-values of the length of the cut, and the output consists of the radius R, and origin (xo,yo). The circle is plotted together with the pelvis plot in x,y-direction in a figure (Fig. 10.)

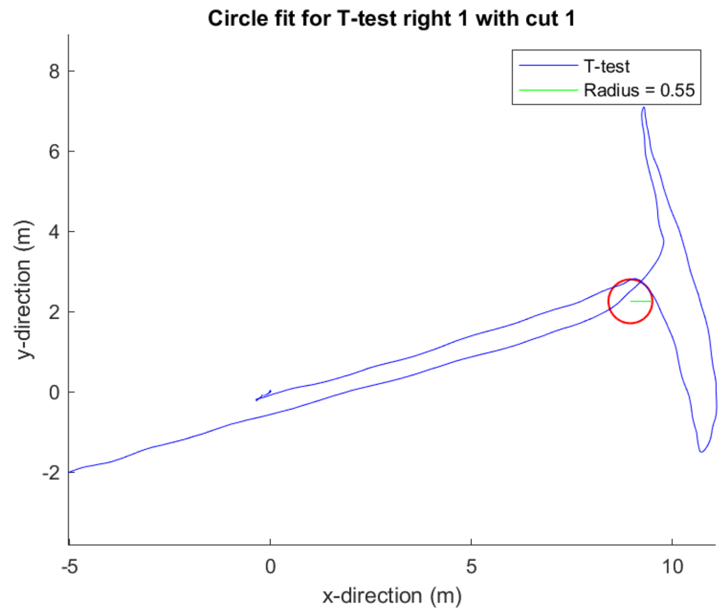


Figure 10: Circle fit for T-test right 1, with the circle fitted in red and Rcirc in green for cut 1.

The sharpness of the 180°cuts (cut2 and cut3 in Fig. 1) is calculated in a different way. This is because those cuts are not suitable to approximate with a circle. A visual analysis has showed that a sharper cut leads to a smaller distance between the incoming and outgoing trajectory, and vice versa. Therefore, the average distance between the incoming and outgoing trajectory is calculated. The plot first needs to be rotated, such that the ’T’ shape is standing upright (Fig. 11). This is done by taking the datapoints of the first straight line, which is from the start until cut1, and taking a linear fit. This linear fit can be used to calculate the rotating angle, and rotate all the datapoints accordingly.

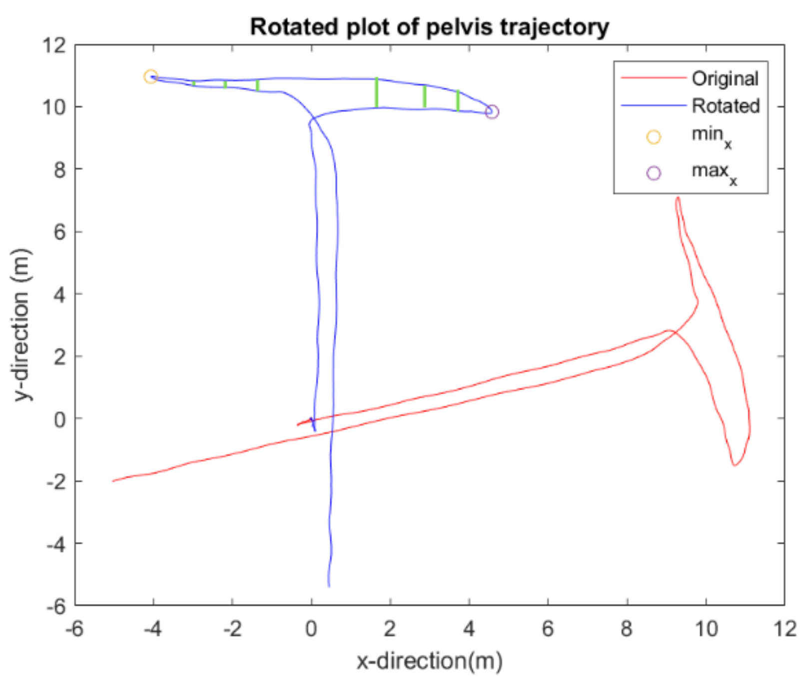


Figure 11: The original trajectory in red, and the rotated trajectory in blue. Both starting points are in the origin. The yellow and purple marker indicate the middle of the 180°cuts, which corresponds to the minimum and maximum x-value. The green vertical lines are an example of the distance taken to calculate the average distance.

The length of the array of datapoints used is defined by taking the minimum and maximum x-value (which corresponds with the furthest points of the T-test in Fig. 11), and the number of datapoints until the end of cut1 or cut4 is reached. From the middle of the cut (minimum or maximum x-value), a step is taken by taking one datapoint plus and one datapoint minus the middle. The difference in y-value is calculated, which correspond with the distance in meters. The average of all the separate differences is taken.

5 Results

5.1 Selection of frames

The results of the comparison of the foot contacts as found by the camera and Xsens can be seen in Table 7. The difference in frames of the initial contact (IC) and toe-off (TO) is calculated based on columns 2, 3, 5 and 6. The average difference is displayed on the bottom of the table. The average difference for the IC and TO is respectively 1.375 and -2.375 frames. This corresponds with an average difference of 1.375 and -2.375 milliseconds.

Table 7: Results of the comparison between the camera and Xsens of the initial contact (IC) and toe-off (TO). Columns 2-7 are expressed in frames, with a framerate of 100 fps, where the (average) difference in frames is calculated.

Test	IC (Camera)	IC (Xsens)	Difference IC camera and Xsens	TO (Camera)	TO (Xsens)	Difference TO camera and Xsens
10_1	2761	2766	5	2847	2845	-2
10_2	1488	1486	-2	1550	1543	-7
10_3	1247	1249	2	1322	1321	-1
10_4	1219	1219	0	1316	1309	-7
10_5	1180	1185	5	1250	1252	2
10_6	1248	1252	4	1308	1309	1
10_7	1284	1283	-1	1352	1353	1
10_8	1285	1283	-2	1359	1353	-6
Average			1.375			-2.375

5.2 Sharpness of the cuts

Before the results are presented, it is important to know which leg is the cutting leg per cut. An overview is made of each cut which shows the used cutting leg (Table 8). It appeared that every participant has a different way of choosing their cutting leg. With these results, the reference side (non-affected side) can be compared with the affected side.

Table 8: Overview of used leg as cutting leg per cut, where L is the left leg and R is the right leg. The preffered cutting leg is the leg which is used the most as cutting leg.

Participant	Trial	Cutting leg				Preffered cutting leg	Affected side
		Cut 1	Cut 2	Cut 3	Cut 4		
1	R1	L	R	R	L	L	R
	R2	L	R	R	L		
	L1	R	L	L	R		
	L2	R	L	L	R		
2	R1	L	L	L	L	L	L
	R2	L	L	L	L		
	L1	R	L	L	R		
	L2	R	L	L	R		
3	R1	L	L	L	L	L	R
	R2	L	L	L	L		
	L1	R	R	L	R		
	L2	R	L	L	R		
4	R1	L	L	R	L	R	R
	R2	L	L	R	L		
	L1	R	R	R	R		
	L2	R	R	R	R		

The radius of the best fit circle of cut1 and cut4 per test is displayed in Table 9. Some cuts do not have a result. This is due to an incorrect measurement. The results showed a 'drift' in the trajectory, such that the starting- and endpoint were not the same (Fig. 12).These cells are marked with an 'X'. A visual example of the fitted circles is shown in Figure 13.

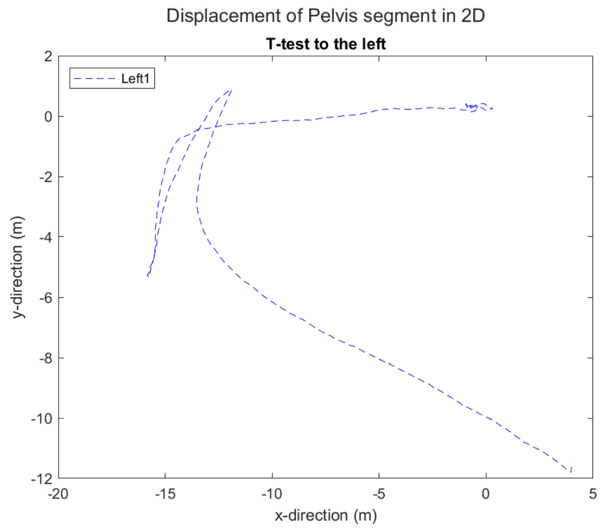
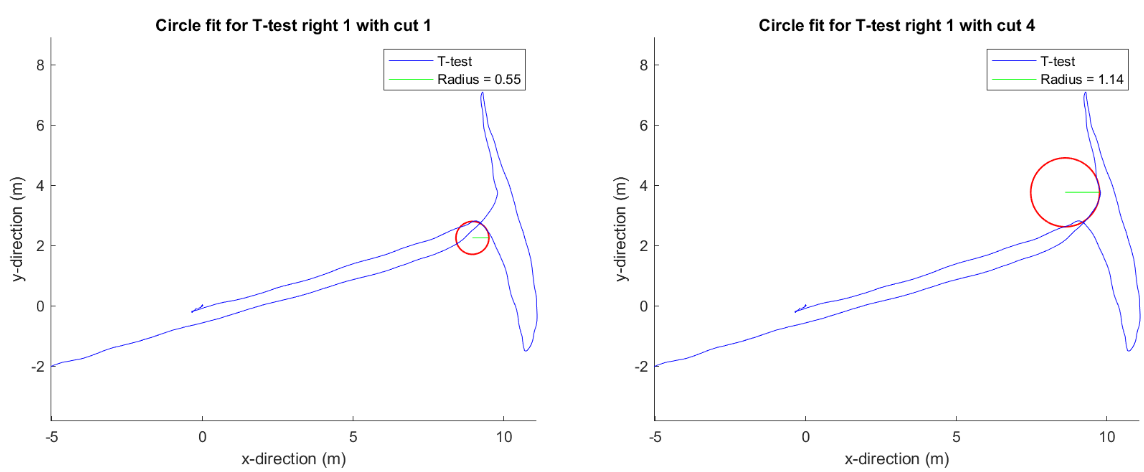


Figure 12: Example of an incorrect measurement

Table 9: Radius in meters of the best fit circle. r1 and r2 are respectively T-test right 1 and 2. l1 and l2 are respectively T-test left 1 and 2.

	Cut1_r1	Cut4_r1	Cut1_r2	Cut4_r2	Cut1_l1	Cut4_l1	Cut1_l2	Cut4_l2
Participant 1	0.55	1.14	1.03	0.74	0.87	0.63	0.55	0.84
Participant 2	1.58	1.24	1.71	1.13	X	0.97	1.26	1.35
Participant 3	1.99	1.45	X	1.13	1.54	1.64	0.79	1.24
Participant 4	1.26	1.94	1.51	2.20	X	X	X	X



(a)

(b)

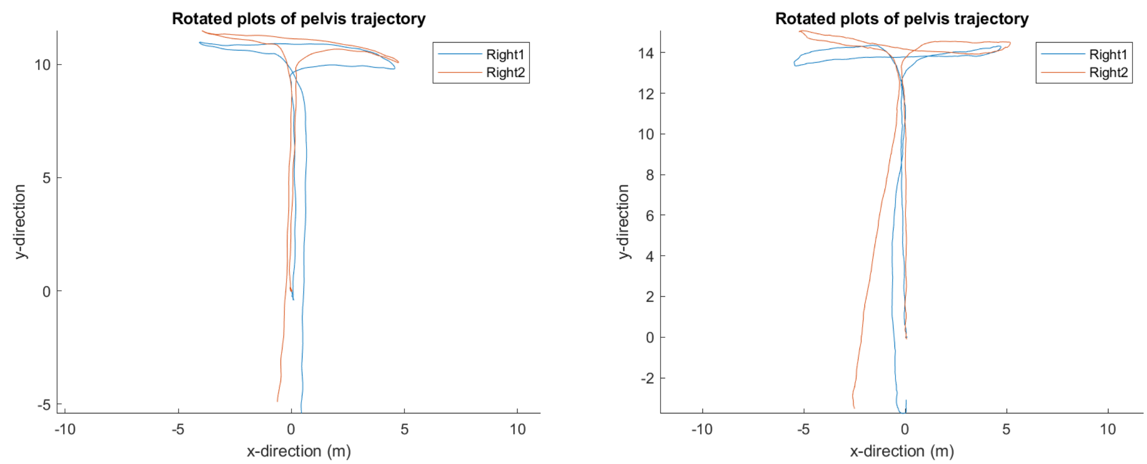
Figure 13: Example of the differences in circle radius between cut 1 and cut 4 of T-test right 1

The average distance between the incoming and outgoing trajectory, which are cut2 and cut3, are displayed in Table 10. Again, some cuts do not have a result, due to the same reason as the 90°cuts

(Fig. 12). These cells are marked with an 'X'. Figure 14 gives a visual representation of the differences in distance of the incoming and outgoing trajectory.

Table 10: Average distance in meters between incoming and outgoing trajectory. r1 and r2 are respectively T-test right 1 and 2. l1 and l2 are respectively T-test left 1 and 2.

	Cut2_r1	Cut3_r1	Cut2_r2	Cut3_r2	Cut2_l1	Cut3_l1	Cut2_l2	Cut3_l2
Participant 1	0.63	0.18	0.28	0.10	0.65	0.89	0.63	0.85
Participant 2	0.33	0.39	0.49	0.21	0.62	0.92	0.92	0.51
Participant 3	0.17	0.46	0.37	0.09	X	0.18	0.74	0.15
Participant 4	0.37	0.23	0.26	0.02	X	X	0.31	0.14

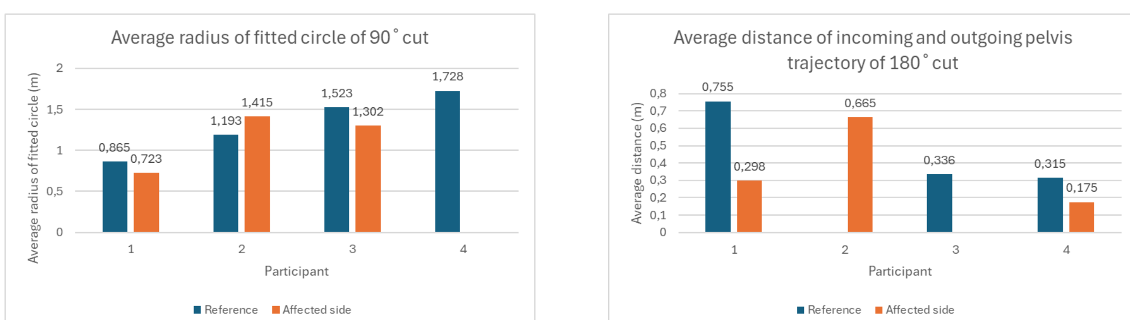


(a) Overlay of T-test right 1 and 2 of participant 1

(b) Overlay of T-test right 1 and 2 of participant 3

Figure 14: Overlays of the trajectory to give a visual representation of the differences

When combining the data from Table 8, 9 and 10, a comparison can be made between the reference side and the affected side (Fig. 15).



(a) Average radius of reference and affected side of 90°cuts

(b) Average distance of reference and affected side of 180°cuts

Figure 15: Comparison of reference and affected side for 90°cuts (a) and 180°cuts (b)

6 Discussion

The first goal of this research was to find new parameters which can be measured during an agility T-test, and could indicate a difference between the affected and non-affected side. The parameter distance had only be used during hop tests, but not during an agility T-test. Therefore, this was a new parameter that was implemented in this research.

Secondly, a data algorithm had to be developed to automatically process the data. This goal has also been reached. A way is found to be able to rotate all the data equally, and therefore it was possible to measure the best fit circle and distances automatically (Fig. 10 and 11). There are some limitations which could improve this research if they were to be solved. These limitations are explained below.

For the data processing part, the selection of the frames of the camera and Xsens is now almost perfect. The average difference is 1 to 2 milliseconds, which is negligible for this experiment(Table 7). However, there are some factors which could influence this small difference. Currently, the synchronization of the frames is done manually. A small offset in the synchronization means a small offset in the results. Also, the video software processed the video in 60 fps, while Xsens recorded in 100 fps. Matching the framerate to 100 fps could decrease the differences. Lastly, there could be displacement of the sensors during the measurements, which result in a different point of ground contact recorded by Xsens (Fig. 8).

The data analysis part also had some limitations. There are some factors that could have affect the results of the measurements. Firstly, the weather conditions can be of influence. Mainly the wind can have an impact. It can result in the participant going faster in one direction than the other, and thus cut in a different way. Also the fitness and fatigue could have an influence. The fitness differs per participant, also based on where they are in their rehabilitation process. Already present fatigue is also important to notice. Some participants already had done a full field training, before performing the measurements while some had only done a warming-up.

The length of the 90°cut is now generalized for every participant to 30 frames above and below the middle of the cut. The choice for 30 frames is based on trial and error, where there was looked at how well the circle fit lined up with the pelvis trajectory. The perfect way would be to find the exact foot contacts of each measurement, and selecting the cut length. However, it appeared that every participant approached the cut in a different way. Therefore, it was out of the scope of this project to find a solution to select the correct foot contacts. In further research, this could be done.

Currently, the data of only 4 participants is available. Some of the data is not usable, because the measurements went wrong (Fig. 12). The pelvis trajectory seems to shift during the measurements. The cause of this is unknown. However, there can be a small trend seen in the results. The cuts done with the affected side, seem to be sharper (lower circle radius and lower average distance) (Fig. 15). Therefore, a possible hypotheses can be: 'Cuts done with the affected side as cutting leg will be sharper than cuts done with the non-affected side, due to the stiffness in the leg of the affected side'.

7 Conclusion

From the literature review it can be concluded that the hop tests and strength test are the most used tests, due to their proven effectiveness in the literature. For the hop tests, distance and time are the measured parameters. For the strength tests, the average power, PT/BW ratio and the H/Q ratio are the most important parameters. The distance was not yet used as parameter for the agility T-test.

The results show that the selection of frames by Xsens to find the foot contacts is accurate enough for this research. The offset is on average between 1 and 3 milliseconds, which is a negligible difference (Table 7).

The measurements showed that there is a difference in the sharpness of the cut during the T-test. When a participant uses the affected side as cutting leg, the cut is sharper (i.e. smaller radius of fitted circle and smaller average distance of incoming and outgoing trajectory of 180°cut) (Fig. 15). It also appeared that participants have a different preferred cutting leg, and that there is not a pattern in which leg is chosen for each cut (Table 8).

A Appendix

A.1 Main script

```
close all
clear all

% Load data patient
text = {'Participant 1'};
affected_side='Rechts'
if strcmp(affected_side, 'Links')
    legendentries = {'Affected attempt 1', 'Affected attempt 2', 'Non-
       affected attempt 1', 'Non-affected attempt 2'};
    legendentries_combi={'Affected Cut 1 A1','Affected Cut 4 A1','
       Affected Cut 1 A2','Affected Cut 4 A2','Non-affected Cut 1 A1',
       'Non-affected Cut 4 A1','Non-affected Cut 1 A2','Non-affected
       Cut 4 A2', 'Initial contact'}
elseif strcmp(affected_side, 'Rechts')
    legendentries = {'Non-affected attempt 1', 'Non-affected attempt 2
       ', 'Affected attempt 1', 'Affected attempt 2'};
    legendentries_combi={'Non-affected Cut 1 A1','Non-affected Cut 4
       A1','Non-affected Cut 1 A2','Non-affected Cut 4 A2','Affected
       Cut 1 A1','Affected Cut 4 A1','Affected Cut 1 A2','Affected Cut
        4 A2','Initial contact'}
end

path_pictures = ['C:\Users\Lizwa\OneDrive - University of Twente\
   Utwente\Bsc 3\Bacheloropdracht\Matlab figures'];

%% Change the filename here to the name of the file you would like to
   import
path_docs=addpath('C:\Users\Lizwa\OneDrive - University of Twente\
   Utwente\Bsc 3\Bacheloropdracht\Current script\Current script\
   Participant 1\')
ttest_right_1 = load_mvnx('ttest_right-001');
ttest_right_2 = load_mvnx('ttest_right-002');
ttest_left_1 = load_mvnx('ttest_left-001');
ttest_left_2 = load_mvnx('ttest_left-002');

%% find cuts
[trough_locs_r1, trough_locs_r2, trough_locs_l1, trough_locs_l2] =
   find_cuts(ttest_right_1, ttest_right_2, ttest_left_1, ttest_left_2,
   path_pictures)


%% Calculate corresponding frames
[f_X_bc, f_X_ec, f_c_bs, f_c_bc, f_c_ec] = frames(fps_camera,
   fps_Xsens, frame_camera_begin_squat, frame_camera_begin_cut,
   frame_camera_end_cut);

%% Plot pelvis displacement and position
pelvis_trajectory_2(ttest_right_1, ttest_right_2, ttest_left_1,
   ttest_left_2, path_pictures, f_X_bc, f_X_ec);

%% find foot contact
[ic_cuts,to_cuts]=foot_contact(ttest_right_1,f_X_bc,f_X_ec);
```

```
%% Plot corresponding video frames
Videoreader(filename1, filename2, f_c_bc, f_c_ec);

%% Best fit circle
cut1_r1 = trough_locs_r1(1);
cut4_r1 = trough_locs_r1(4);
cut1_l1 = trough_locs_l1(1);
cut4_l1 = trough_locs_l1(4);
cut1_r2 = trough_locs_r2(1);
cut4_r2 = trough_locs_r2(4);
cut1_l2 = trough_locs_l2(1);
cut4_l2 = trough_locs_l2(4);
cut = cut1_r1;  % Define specific cut needed
filename = ttest_right_1;      % Define specific file needed
[xo, yo, R] = circle_fit(filename.segmentData(1).position((cut-30):(
    cut+30), 1),filename.segmentData(1).position((cut-30):(cut+30), 2),
     filename, cut);

%% Rotation
[R_matrix, D_matrix, p, F1, F2, min_idx, differences_c2,
    differences_c3, avg_dif_c2, avg_dif_c3] = Rotation(filename1,
    filename2, cut1_r1, cut4_r1, cut1_l2, cut4_l2);
```

A.2 Functions needed for data processing

```
function [f_X_bc, f_X_ec, f_c_bs, f_c_bc, f_c_ec] = frames(fps_camera,
     fps_Xsens, frame_camera_begin_squat, frame_camera_begin_cut,
    frame_camera_end_cut)
% This function calculates the frames of the Xsens that correspond to
    the
% frames of the camera.

    fps_c = fps_camera;      % Framerate of camera
    fps_X = fps_Xsens;       % Framerate of Xsens

    f_c_bs = frame_camera_begin_squat;      % Frame where squat is a
        lowest point, needed for synchronization
    f_c_bc = frame_camera_begin_cut;
    f_c_ec = frame_camera_end_cut;

    f_X_bc = round(f_c_bs+((fps_X/fps_c)*f_c_bc)); %f_X_bc =
        frame_Xsens_begin_cut
    f_X_ec = round(f_c_bs+((fps_X/fps_c)*f_c_ec)); %f_X_ec =
        frame_Xsens_end_cut

end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


function pelvis_trajectory_2(ttest_right_1, ttest_right_2,
    ttest_left_1, ttest_left_2, path_pictures, f_X_bc, f_X_ec)
% In this function, we plot the position of the pelvis segment in 3D
    and
```

```
% the displacement of the pelvis segment for all four attempts (twice
    the
% 'Change-of-direction T-test' to the left, twice to the right

%% Plot trajectory
% Plot 3D displacement of segment 1
    figure('name','Position of first segment in 3D','Position',[0,
        100, 2000, 500])
    tiledlayout(1, 4);
    sgtitle('Position of pelvis segment in space')

    nexttile;
    plot(ttest_right_1.segmentData(1).position(:,1),'-b')
    %plot markers begin and end cut
    hold on
    y1 = ttest_right_1.segmentData(1).position(f_X_bc,1);
    plot(f_X_bc,y1,'o')
    y2 = ttest_right_1.segmentData(1).position(f_X_ec,1);
    plot(f_X_ec,y2,'o')
    axis tight
    ylabel('x-direction (m)')
    xlabel('Frame')
    legend('T test','Begin cut','End cut')
    title ('Displacement of pelvis segment in space (x-direction)')

    nexttile;
    plot(ttest_right_1.segmentData(1).position(:,2),'-b')
    %plot markers begin and end cut
    hold on
    y3 = ttest_right_1.segmentData(1).position(f_X_bc,2);
    plot(f_X_bc,y3,'o')
    y4 = ttest_right_1.segmentData(1).position(f_X_ec,2);
    plot(f_X_ec,y4,'o')
    ylabel('y-direction (m)')
    xlabel('Frame')
    legend('T test','Begin cut','End cut')
    title ('Displacement of pelvis segment in space (y-direction)')

    nexttile([1,2]);
    plot(ttest_right_1.segmentData(1).position(:,3),'-b')
    %plot markers begin and end cut
    hold on
    y5 = ttest_right_1.segmentData(1).position(f_X_bc,3);
    plot(f_X_bc,y5,'o')
    y6 = ttest_right_1.segmentData(1).position(f_X_ec,3);
    plot(f_X_ec,y6,'o')
    ylabel('z-direction (m)')
    xlabel('Frame')
    legend('T test','Begin cut','End cut')
    title ('Displacement of pelvis segment in space (z-direction)')
    filename='Displacement_pelvis.png'
    full_path = fullfile(path_pictures, filename);
    % Save the figure with the specified filename and path
    saveas(gcf, full_path);
    %% Read the data from the structure e.g. segment 1
    % Plot 3D displacement of segment 1
```

```
figure('name','Position of first segment in 3D','Position',[100,
    100, 1800, 800])
plot3(ttest_right_1.segmentData(1).position(:,1),ttest_right_1.
    segmentData(1).position(:,2),ttest_right_1.segmentData(1).
    position(:,3),'-b');
%plot markers begin and end cut
hold on
plot3(ttest_right_1.segmentData(1).position(f_X_bc,1),
    ttest_right_1.segmentData(1).position(f_X_bc,2),ttest_right_1.
    segmentData(1).position(f_X_bc,3),'o')
plot3(ttest_right_1.segmentData(1).position(f_X_ec,1),
    ttest_right_1.segmentData(1).position(f_X_ec,2),ttest_right_1.
    segmentData(1).position(f_X_ec,3),'o')
xlabel('x-direction (m)')
ylabel('y-direction (m)')
zlabel('z-direction (m)')
title ('Displacement of Pelvis segment in space')
legend('T test','Begin cut','End cut')
filename='Displacement_pelvis_space.png'
full_path = fullfile(path_pictures, filename);
% Save the figure with the specified filename and path
saveas(gcf, full_path);

%% Plot data in x,y-direction
figure('name', 'Displacement of Pelvis segment in 2D', 'Position'
    ,[0, 100, 2000, 500])
tiledlayout(1,3);
sgtitle('Displacement of Pelvis segment in 2D')

%Plot the 2 attempts to the right
nexttile;
plot(ttest_right_1.segmentData(1).position(:,1), ttest_right_1.
    segmentData(1).position(:,2), '-b');
hold on
plot(ttest_right_2.segmentData(1).position(:,1), ttest_right_2.
    segmentData(1).position(:,2), '-r');
xlabel('x-direction (m)')
ylabel('y-direction (m)')
legend('Right1', 'Right2', 'Location', 'northwest')
title ('T-test to the right')

%Plot the 2 attempts to the left
nexttile;
plot(ttest_left_1.segmentData(1).position(:,1), ttest_left_1.
    segmentData(1).position(:,2), '--b');
hold on
plot(ttest_left_2.segmentData(1).position(:,1), ttest_left_2.
    segmentData(1).position(:,2), '--r');
xlabel('x-direction (m)')
ylabel('y-direction (m)')
legend('Left1', 'Left2', 'Location', 'northwest')
title ('T-test to the left')

%Plot all 4 attempts
nexttile;
plot(ttest_right_1.segmentData(1).position(:,1), ttest_right_1.
```

```
        segmentData(1).position(:,2), '-b');
    hold on
    plot(ttest_right_2.segmentData(1).position(:,1), ttest_right_2.
        segmentData(1).position(:,2), '-r');
    plot(ttest_left_1.segmentData(1).position(:,1), ttest_left_1.
        segmentData(1).position(:,2), '--b');
    plot(ttest_left_2.segmentData(1).position(:,1), ttest_left_2.
        segmentData(1).position(:,2), '--r');
    xlabel('x-direction (m)')
    ylabel('y-direction (m)')
    legend( 'Right1', 'Right2', 'Left1', 'Left2', 'Location', '
        northwest' )
    title ('T-test to the right and left')
    filename='Displacement_pelvis_2D.png'
    full_path = fullfile(path_pictures, filename);
    % Save the figure with the specified filename and path
    saveas(gcf, full_path);

end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


function Videoreader(filename1, filename2, f_c_bc, f_c_ec)
% This function reads the video's and displays the frames which
   correspond
% to the selected foot contacts.

%Add filename of video to read
vidObj = VideoReader(filename1);
vidObj2 = VideoReader(filename2);

%Starting time of video in seconds
vidObj.CurrentTime = 0;
vidObj2.CurrentTime = 0;

figure("Name",'Corresponding video frames')
subplot(2,2,1)
frame_1 = read(vidObj, f_c_bc);
imshow(frame_1)
title('Frame of begin cut')
subplot(2,2,2)
frame_2 = read(vidObj, f_c_ec);
imshow(frame_2)
title('Frame of end cut')
subplot(2,2,3)
frame_3 = read(vidObj2, f_c_bc);
imshow(frame_3)
title('Frame of begin cut')
subplot(2,2,4)
frame_4 = read(vidObj2, f_c_ec);
imshow(frame_4)
title('Frame of end cut')
```

A.3 Functions needed for data analysis

```
function [trough_locs_r1, trough_locs_r2, trough_locs_l1,
    trough_locs_l2] = find_cuts(ttest_right_1, ttest_right_2,
    ttest_left_1, ttest_left_2,path_pictures)
    % Cuts are determined by a drop in the height of the pelvis segment
    % (z-direction).
     %% CoD T-test to the right, attempt 1
     [troughs_r1, trough_locations_r1] = findpeaks(-ttest_right_1.
        segmentData(1).position(:,3),'MinPeakDistance',80,'
        MinPeakProminence',0.1);
     % Sort the values and keep track of the original indices
     [sorted_values_r1, sorted_indices_r1] = sort(troughs_r1,'descend')
        ;
     % % Retrieve the four smallest values
     smallest_four_r1 = sorted_values_r1(1:4);
     smallest_indices_r1 = sorted_indices_r1(1:4);
     sorted_indices_r1 = sort(smallest_indices_r1);
     trough_r1=troughs_r1(sorted_indices_r1);
      % Retrieve the corresponding x-values
     trough_locs_r1 = (trough_locations_r1(sorted_indices_r1));
     %trough_locs_r1=[451,599,841,991];
     %% CoD T-test to the right, attempt 2
     [troughs_r2, trough_locations_r2] = findpeaks(-ttest_right_2.
        segmentData(1).position(:,3),'MinPeakDistance',80,'
        MinPeakProminence',0.1);
     % Sort the values and keep track of the original indices
     [sorted_values_r2, sorted_indices_r2] = sort(troughs_r2,'descend')
        ;
     % Retrieve the four smallest values
     smallest_four_r2 = sorted_values_r2(1:4);
     smallest_indices_r2 = sorted_indices_r2(1:4);
     sorted_indices_r2 = sort(smallest_indices_r2);
     trough_r2=troughs_r2(sorted_indices_r2);
     % Retrieve the corresponding x-values
     trough_locs_r2 = trough_locations_r2(sorted_indices_r2);
     %trough_locs_r2=[661, 804,1048,1198];
     %% CoD T-test to the left, attempt 1
     [troughs_l1, trough_locations_l1] = findpeaks(-ttest_left_1.
        segmentData(1).position(:,3),'MinPeakDistance',80,'
        MinPeakProminence',0.1);
     % Sort the values and keep track of the original indices
     [sorted_values_l1, sorted_indices_l1] = sort(troughs_l1,'descend')
        ;
     % % Retrieve the four smallest values
     smallest_four_l1 = sorted_values_l1(1:4);
     smallest_indices_l1 = sorted_indices_l1(1:4);
     sorted_indices_l1 = sort(smallest_indices_l1);
     trough_l1=troughs_l1(sorted_indices_l1);
     % Retrieve the corresponding x-values
     trough_locs_l1 = trough_locations_l1(sorted_indices_l1);
     %trough_locs_l1=[524, 658,904,1054];
     %% CoD T-test to the left, attempt 2
     [troughs_l2, trough_locations_l2] = findpeaks(-ttest_left_2.
        segmentData(1).position(:,3),'MinPeakDistance',80,'
        MinPeakProminence',0.1);
     % Sort the values and keep track of the original indices
```

```
    [sorted_values_l2, sorted_indices_l2] = sort(troughs_l2,'descend')
        ;
    %Retrieve the four smallest values
    smallest_four_l2 = sorted_values_l2(1:4);
    smallest_indices_l2 = sorted_indices_l2(1:4);
    sorted_indices_l2 = sort(smallest_indices_l2);
    trough_l2=troughs_l2(sorted_indices_l2);
    % Retrieve the corresponding x-values
    trough_locs_l2 = trough_locations_l2(sorted_indices_l2);
    %trough_locs_l2=[570,687,928,1078];
%% plot
figure('Name','Z-direction Pelvis','Position', [100, 100, 1800, 800]);
tiledlayout(2,2);
sgtitle('Pelvis height during attempts');
nexttile
plot(ttest_left_1.segmentData(1).position(:,3),'-r');
hold on
scatter(trough_locs_l1,ttest_left_1.segmentData(1).position(
   trough_locs_l1,3))
% scatter(trough_locs_l1,-trough_l1)
xlabel('Frame')
ylabel('Pelvis height (m)')
title('T-test to left, attempt 1')
nexttile
plot(ttest_right_1.segmentData(1).position(:,3),'-b');
title('T-test to right, attempt 1')
hold on
scatter(trough_locs_r1,ttest_right_1.segmentData(1).position(
   trough_locs_r1,3))
%scatter(trough_locs_r1,-trough_r1)
xlabel('Frame')
ylabel('Pelvis height (m)')
nexttile
plot(ttest_left_2.segmentData(1).position(:,3),'Color',"#FF7377");
hold on
%scatter(trough_locs_l2,-trough_l2)
scatter(trough_locs_l2(1),ttest_left_2.segmentData(1).position(
   trough_locs_l2(1),3),'r')
scatter(trough_locs_l2(2),ttest_left_2.segmentData(1).position(
   trough_locs_l2(2),3),'y')
scatter(trough_locs_l2(3),ttest_left_2.segmentData(1).position(
   trough_locs_l2(3),3),'b')
scatter(trough_locs_l2(4),ttest_left_2.segmentData(1).position(
   trough_locs_l2(4),3),'g')
xlabel('Frame')
title('T-test to left, attempt 2')
ylabel('Pelvis height (m)')
nexttile
plot(ttest_right_2.segmentData(1).position(:,3),'-','Color',"#4DBEEE")
    ;
hold on
scatter(trough_locs_r2,ttest_right_2.segmentData(1).position(
   trough_locs_r2,3))
title('T-test to right, attempt 2')
xlabel('Frame')
ylabel('Pelvis height (m)')
```

```
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [ic_cuts,to_cuts]=foot_contact(ttest_right_1,f_X_bc,f_X_ec)
%%
% load foot contact data from XSens file, where 1 equals foot contact
    and 0
% equals no contact
righttoe=ttest_right_1.footContact(4).footContacts(:);
rightheel=ttest_right_1.footContact(3).footContacts(:);
lefttoe=ttest_right_1.footContact(2).footContacts(:);
leftheel=ttest_right_1.footContact(1).footContacts(:);

% Find contacts of left foot, where find returns non-zero elements
[toe_left,~]=find(lefttoe);
[heel_left,~]=find(leftheel);

footcontact_left=sort([toe_left;heel_left]); % merge heel and toe
    contacts
fc_left=unique(footcontact_left); % remove duplicates

% Determine initial contacts and toe-offs of left foot
ic_cuts_left=[];
to_cuts_left=[];
for i = 2:numel(fc_left)
    if fc_left(i) - fc_left(i-1) > 1 % Find non-consecutive frames, as
        gaps in frames indicate there was no foot-contact
        ic_cuts_left = [ic_cuts_left,fc_left(i)];
        to_cuts_left= [to_cuts_left,fc_left(i-1)];
    end
end
ic_cuts.left=ic_cuts_left; % Save Initial Contact frames in workspace
to_cuts.left=to_cuts_left; % Save Toe-off frames in workspace

% Find contacts of right foot
[toe_right,~]=find(righttoe);
[heel_right,~]=find(rightheel);

footcontact_right=sort([toe_right;heel_right]); % merge heel and toe
    contacts
fc_right=unique(footcontact_right); % remove duplicates

% Determine initial contacts and toe-offs of right foot
ic_cuts_right=[];
to_cuts_right=[];
for i = 2:numel(fc_right)
    if fc_right(i) - fc_right(i-1) > 1
        ic_cuts_right = [ic_cuts_right,fc_right(i)];
        to_cuts_right= [to_cuts_right,fc_right(i-1)];
    end
end
ic_cuts.right=ic_cuts_right;
```

```
to_cuts.right=to_cuts_right;


    figure('Name', 'Map of foot contact during cutting maneuver', '
       Position', [100, 100, 1800, 800]);
    sgtitle('Map of foot contact during cut')
    % Find initial contacts during cutting maneuver of left leg
    cut_ic_left= ic_cuts_left(ic_cuts_left >= (f_X_bc-40) &
       ic_cuts_left <= (f_X_ec+40)); % +40 and -40 frames to show all
       contacts around cutting time
    cut_to_left= to_cuts_left(to_cuts_left >= (f_X_bc-40) &
       to_cuts_left <= (f_X_ec+40));

    % Find initial contacts during cutting maneuver of right leg
    cut_ic_right= ic_cuts_right(ic_cuts_right >= (f_X_bc-40) &
       ic_cuts_right <= (f_X_ec+40));
    cut_to_right= to_cuts_right(to_cuts_right >= (f_X_bc-40) &
       to_cuts_right <= (f_X_ec+40));

        hold on;
        plot(ttest_right_1.segmentData(1).position(f_X_bc:f_X_ec,3))
        scatter(cut_ic_left-f_X_bc,ttest_right_1.segmentData(1).
           position(cut_ic_left-1,3),'red','filled','o')
        scatter(cut_to_left-f_X_bc,ttest_right_1.segmentData(1).
           position(cut_to_left-1,3),'red','d')
        scatter(cut_ic_right-f_X_bc,ttest_right_1.segmentData(1).
           position(cut_ic_right-1,3),'blue','filled','o')
        scatter(cut_to_right-f_X_bc,ttest_right_1.segmentData(1).
           position(cut_to_right-1,3),'blue','d')

        axis padded;
        xlabel('Frame')
        ylabel('z-direction (m)')
        legend('Pelvis trajectory','Initial contact','Toe-off','
           Location','northeastoutside')
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


function [xo, yo, R] = circle_fit(x,y, filename, cut)
% This function calculates the best fit circle for the 90 degree cut
   based on the least squares
% method

    % Calculate the best fit circle
    A = [-2*x -2*y ones(length(x),1)];
    x = A\-(x.^2+y.^2);
    xo=x(1);
    yo=x(2);
    R = sqrt(  xo.^2 + yo.^2  - x(3));
    origin = [xo yo];
    endPoint = [xo+R yo];
```

```
    figure();
    hold on
    viscircles([xo yo], R, 'Color', 'r', 'Linewidth', 1); % Plot the
        best fit circle
    plot(filename.segmentData(1).position(:,1), filename.segmentData
        (1).position(:,2), '-b'); %Plot pelvis trajectory
    plot([origin(1), endPoint(1)], [origin(2), endPoint(2)], '-g'); %
        Plot radius of circle in figure
    xlabel('x-direction (m)')
    ylabel('y-direction (m)')
    title('Circle fit for T-test right 2 with cut 4');
    legend('T-test', sprintf('Radius = %.2f', R))
    axis equal
    hold off


end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


function [R_matrix, D_matrix, p, F1, F2, min_idx, differences_c2,
    differences_c3, avg_dif_c2, avg_dif_c3] = Rotation(filename1,
    filename2, cut1_r1, cut4_r1, cut1_l1, cut4_l1)
% This function rotates the plots, such that the 'T'-shape is in an
    upright
% position. It then calculates the average distance bewteen the
    incoming
% and outgoing trajectory of the 180 degree cuts.

%% Create linear fit and rotate plots
figure();
hold on;


for filename = [filename1 filename2]
    % Select datapoints to create linear fit
    x = filename.segmentData(1).position(1:400,1);
    y = filename.segmentData(1).position(1:400,2);

    % Align plot to (0,0)
    aligned_position_x = filename.segmentData(1).position(:,1) -
        filename.segmentData(1).position(1,1);
    aligned_position_y = filename.segmentData(1).position(:,2) -
        filename.segmentData(1).position(1,2);

    % Perform linear fit
    c = polyfit(x, y, 1);
    fitted_y = polyval(c, x);

    plot(x, fitted_y, '-b');
    plot(aligned_position_x, aligned_position_y, '-r');
end

legend('Fitted line', 'Aligned positions');
```

```matlab
title('Linear fit of first segment of pelvis trajectory')
xlabel('x-direction (m)');
ylabel('y-direction (m)');
hold off;


figure();
hold on;

for filename = [filename1 filename2]
    % Select datapoints to create linear fit
    x = filename.segmentData(1).position(1:1000,1);
    y = filename.segmentData(1).position(1:1000,2);

    % Align plot to (0,0)
    aligned_position_x = filename.segmentData(1).position(:,1) -
       filename.segmentData(1).position(1,1);
    aligned_position_y = filename.segmentData(1).position(:,2) -
       filename.segmentData(1).position(1,2);

    % Perform linear fit
    c = polyfit(x, y, 1);

    % Calculate angle for rotation
    B = atand(abs(c(1)));     % c(1) is equal to the slope of the
       linear fit

    % Q1: 90-B, Q2 = -Q1, Q3: -B-90, Q4 = -Q3
    theta = 90-B;

    % Create rotation and data matrix
    R_matrix = [cosd(theta) -sind(theta); sind(theta) cosd(theta)];
    D_matrix = [filename.segmentData(1).position(:,1), filename.
       segmentData(1).position(:,2)];

    % Perform rotation
    p = (R_matrix*D_matrix')';
    p_aligned_x = p(:,1)-p(1,1);
    p_aligned_y = p(:,2)-p(1,2);
    p_aligned = [p_aligned_x, p_aligned_y];

    % Plot rotated data
    plot(p_aligned_x, p_aligned_y)
    title('Rotated plot of pelvis trajectory');
    legend('Right1', 'Right2')
end

 axis equal

%% Find average distance between lines
% Find the minimum and maximum x-value and its corresponding y-value
[min_x, min_idx] = min(p_aligned_x);
min_y = p_aligned(min_idx, 2);
[max_x, max_idx] = max(p_aligned_x);
max_y = p_aligned(max_idx, 2);
F1 = [min_x min_y];
```

```
F2 = [max_x max_y];
%Plot the point with the minimum x-value
plot(min_x, min_y, "Marker","o");
hold on
plot(max_x, max_y, "Marker","o");

title('Rotated plots of pelvis trajectory');
legend('Right1', 'Right2', 'min_x', 'max_x');
xlabel('x-direction (m)');
ylabel('y-direction (m)');

    % rechtsom
    max_steps_c2 = abs(max_idx - (cut1_r1+30));  % Calculate length of
         the cut
    max_steps_c3 = abs(min_idx - (cut4_r1-30));

    % linksom
    max_steps_c2 = abs(min_idx - (cut1_l1-30));
    max_steps_c3 = abs(max_idx - (cut4_l1+30));


    differences_c2 = [];    % Create empty array
    differences_c3 = [];

% Calculate difference in distance for cut2
for step = 1:max_steps_c2
    lower_idx = min_idx - step;     % take 1 frame above and below
       min_idx
    upper_idx = min_idx + step;

    lower_y = p_aligned(lower_idx, 2);      % Find corresponding y-
       value
    upper_y = p_aligned(upper_idx, 2);
    y_diff = abs(upper_y-lower_y);      % Calculate difference in y-
       value
    differences_c2 = [differences_c2; y_diff];  % Add calculated value
        to array

end
avg_dif_c2 = average(differences_c2);   % Calculate average distance

% Calculate difference in distance for cut3
for step = 1:max_steps_c3
    lower_idx = max_idx - step;     % take 1 frame above and below
       max_idx
    upper_idx = max_idx + step;

    lower_y = p_aligned(lower_idx, 2);      % Find corresponding y-
       value
    upper_y = p_aligned(upper_idx, 2);
    y_diff = abs(upper_y-lower_y);      % Calculate difference in y-
       value
    differences_c3 = [differences_c3; y_diff];      % Add calculated
       value to array
```

```
end
avg_dif_c3 = average(differences_c3);        % Calculate average
   distance
```

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