Department

Physikalische Technik

Master Thesis

About

Validation of 3D silhouette tracking as clinical movement analysis tool

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Abstract

Recovery from an injury in general is an important topic especially for athletes, but for ordinary people as well. Depending on the degree of severity, it takes a long time to get back to sports. Furthermore, the athlete is not yet in the physical state which is required for competition. Therefore, a lot of return to sport screenings have been established to estimate the biomechanics in injury pattern. In this work an established return to sport screening is used in order to investigate the possibility to settle markerless silhouette-based tracking as a more efficient and objective method for return to sport screenings in the clinical field. Eight subjects perform six high dynamic and static movements in the laboratory. Body joint angles, which are obtained by visual inspection are tracked with the three system-based evaluation methods and rated accordingly to the return to sport scoring. Furthermore, important resulting joint moments in the knee, such as knee abduction moment and internal rotation moment are compared to the single scores from each movement to determine an association. The results show that rater-based tracking measures and therefore scores the subjects higher than the gold standard. Besides, these two methods are not equivalent, which challenges the rater-based return to sport screening. The markerless screening shows a more confident method to substitute the gold standard. Whereas the results of the exact angle measurement are only equivalent for a few movements, the scoring has an almost perfect agreement. The most promising method is the Hybrid tracking, which results in an overall agreement with the marker-based 3D-Motion tracking. The second part of this work reveals a first significant association between knee abduction moment and internal rotation moment and the return to sport scoring. Additionally a good correlation between markerless generated joint moments and marker-based moments has been detected. But the deviation of both methods is partly very high and reveals differences in both tracking methods. These results lead to the conclusion, that markerless silhouette tracking is capable of kinetic data producing, but it needs more complex investigations to verify its full potential. Therefore, markerless tracking puts itself in the best position for return to sport screenings in the clinical field.

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1 Introduction

1.1 Return to Sport and its importance

Modern medicine constantly offers new methods for surgery and rehabilitation in sports. This constant change decreases the time an athlete needs to recover, but this does not mean the athlete is capable of returning immediately. Most of the returnings come along with new injuries or secondary troubles, which are caused by careless and overhasty reentry in sports.[1][2] The most common severe injury in sport is the tear of the anterior cruciate ligament (ACL), which is also considered to be the most devastating.

There are a lot of ACL injuries around the globe, and there is still no real standardization [3] for athletes to return to sport or even to get information of when it is safe to return.[4] There are a lot of factors which have to be considered when trying to return to sport or even getting back to every day activities. Not only does the athlete need to experience the absence of pain and a good range of motion, but also the muscle strength, motion, and stabilization itself are factors which are significant. People start to recognize, that it is even more important to evaluate the biomechanics of movement patterns to pin down the reasons for injury, instead of only healing the symptoms. Nowadays there are two ways to obtain information about biomechanics, rater-based evaluations and high-end marker-based 3D-Motion tracking.

1.2 Problems of rater-based screening

At this point, the sports rehabilitation society tried to develop methods to estimate the capability of a re-injury by the so-called return to sport screenings.[5] To promote screenings in the field or clinical setting, screening tools must be quick and easy to use and should enable the physical therapist or clinician to provide immediate feedback to the athlete.[6][7] Those screenings are mostly performed with two simple video cameras which are set up sagittal and frontal to the subject. The final analysis is done by an objective rater, who validates either the complete movement by its execution, or a single image at a certain point of time by a predefined score. Based on the scoring the clinician or physical therapist tries to draw a conclusion about the physical state of the athlete. Due to the problems of financial setup costs, rater-based screening is the most training and time efficient possibility for the institution.
In order to perform a visual movement analysis the physical therapist has to have a certain level of education. For example, Onate et al.[8] has shown that there is a good agreement in rating sport movements, while comparing novice and experienced rater.

On the other hand, a simple visual inspection can lead to subjectivity and uncertainity.

The rater have to be educated well enough to ensure good definition of anatomical landmarks to identify the right position or movement. It has to be also ensured that all raters are on the same page. Research has shown that with increasing experience the objectivity and reliability improves.[9] In literature, publications which enforce a good inter-rater-reliability[8][10] can be found, but there are as well opposite findings.[11] Ekegren et al.[6] discovered that raters failed to detect up to a third of "truly high-risk" individuals, because of inadequate sensitivity values for the screening methods. Furthermore, he notes that there is a poor agreement by estimating knee valgus with 2-D compared to 3-D motion tracking. A different study, examining runners, showed that angles measured by visual inspection have a poor to substantial inter-rater reliability, such as knee flexion angle ($\kappa_w = 0.00 - 0.68$) or lateral pelvic drop ($\kappa_w = 0.39$).[12] Another aspect is the velocity of the movement. Slower, speed-controlled movements, such as squat movements are better to rate, than faster more explosive movements, such as a drop jump.[13][14] Depending on the velocity of the movement the cameras need to have a high frame rate to capture the whole movement. Otherwise essential parts of the movement are skipped, because of the high speed. Additionally the cameras need to be synchronized and the important body planes (sagittal and frontal) have to be exactly aligned with the camera, otherwise a 2-D measurement is not possible.

But at the end these scores are only an alternative to quantify movement without any 3D-Motion equipment. In conclusion, there are a lot of different return to sport screenings in use[1], but there is no real standardization to build a common screening tool.[3]

1.3 Method of marker-based screening - Pros and Cons

Marker-based tracking is the standard technology of motion capture nowadays. However, there are advantages but also disadvantages of this technology. Markers can be tracked with a very high accuracy. Tests with the Simi Motion 3D system show a mean failure of < 0.1mm.[15] Due to the high capture frame rates even fast and explosive movements can be analyzed easily. Furthermore, through attaching at least three markers to each body segment, movements of all segments in all planes can be represented unambiguously.

However, there are some problems and disadvantages that occur with marker-based tracking. First, the exact placement of markers is difficult to realize. Although there are exact predefined spots where the markers have to be attached, it is impossible to place them on the exact same spots for different measurements conducted by the same or by different examiners. Also, errors occur due to skin and therefore marker movements related to the underlying bones.[16] Additionally it is widely acknowledged that this technique is too time consuming and costly to be used in mass screening programs or clinical use. [6][7]

Basically, there is no big chance for the marker-based tracking in the clinical usage. The time that is needed to place markers was quantified in a little survey among clinicians and scientists, who work with a marker-based system. The participants stated to need an average of 18 min (±7 min) for placing 31 (±7) markers.(Appendix A.1) If many analyses are conducted each day, this is a considerable amount of time. Moreover, if markers are lost during the movement, the whole capturing may have to be repeated. It is also possible that captured subjects change their natural way of movement, as they take care of not losing markers. To conclude, even though markers can be tracked very accurately, by using different protocols or committing small marker placement errors, results can be very different and hard to compare. Furthermore, a considerable amount of time is needed to conduct analyses and subjects may be affected in their usual movement behavior. These are the reasons why marker-based tracking has not settled as tool in clinical application.

1.4 Method of markerless tracking

New markerless tracking offers many advantages compared to marker-based tracking. First, there are no markers that can be placed incorrectly or lead to inaccuracy because of skin artifacts. Second, much time can be saved if no markers have to be attached. This indicates as well that no education or biomechanical knowledge has to be expected to capture movements. Rater-based and marker-based tracking are both based on subjectivity of the user. Marker-based tracking is depending on the knowledge of marker attachment and rater-based needs knowledge of anatomical landmarks as well. Neither the positions of landmarks nor the marker attachment are necessary for silhouette tracking, which enables a more objective data acquisition. Furthermore, the captured subjects are free and undisturbed in their movement. In the end, markerless tracking could solve the problems of marker-based tracking and rater-based screening and could settle as the alternative for the clinical application with the least disadvantages of all evaluation systems. The accuracy is already tested in different laboratory studies. This would be a first move forward evaluating the markerless tracking in the direction of application.

Goal of part I in this thesis is to give an assumption, whether markerless tracking with Simi Shape is a more objective alternative to a difficult and time consuming marker-based tracking, when it comes to return-to-sport evaluations. Therefore, one return to sport screening battery, which is used for 2D-rater-based inspection, is introduced. Furthermore, this thesis investigates the possibility of markerless tracking being accurate and reliable to conduct clinical movement screenings. The return to sport screening serves only as a guideline and is not evaluated in this work.

Part II uses a novel approach to get a glimpse on the joint moment. These are the basis for the return to sport screenings. Because rater-based screenings cannot evaluate dynamic data, the dynamic data, which is gained with markerless tracking is investigated to emphasize the clinical application of markerless silhouette-based tracking.

Part I
Validation of markerless tracking and 2D-rater-based screening against 3D marker-based measurement for return to sport screenings

2 Theoretical background

2.1 Basic anatomy

2.1.1 Anatomical axes and planes

The anatomy uses three major body-axes to describe position and orientation of any segments. All three axes intersect in the center of mass [COM]. The three main axes are the following:

- Transverse-axis: x-axis of the body, going through the COM from the left side to the right
- Longitudinal-axis: y-axis of the body, going from cranial to caudal
- Sagittal-axis: z-axis of the body, going through the body from dorsal to ventral

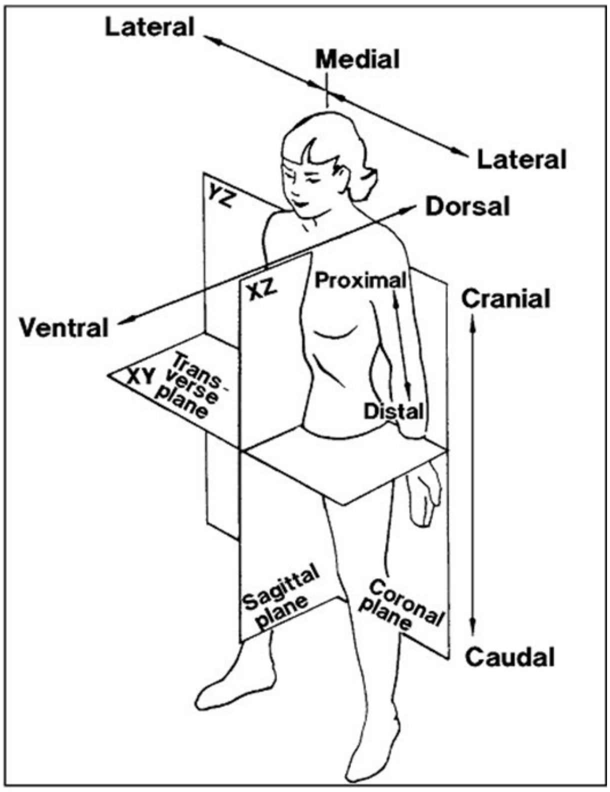

Figure 2.1: Planes and directional terms of the human body[17]

For further description in the anatomy in general and in the context of this work the human body and its motion are defined by three major planes. Each plane is generated by two axes.

- Frontal-plane/Coronal-plane: longitudinal- and transverse-axis
- Sagittal-plane: sagittal- and longitudinal-axis form this plane, which divides the body into two symmetrical halves.
- Transverse-plane: transverse- and sagittal-axis span this plane and divide the body into upper and lower body

2.1.2 Joints of the human body

A joint is a flexible connection between at least two bones. Muscles are connected to the bones by tendons to enable movements. The bones are covered with articular cartilage in order to prevent friction. Additionally, there is the so called 'synovial fluid' located in the joint space between the two bones that, on one hand, ensures a smooth sliding of the bones against each other and on the other hand, supplies the cartilage with nutrients. The joint capsule is a fibrous capsule, which encloses the entire joint and prevents the liquid from pouring out.[18]

One differentiates between various kinds of joints, which are characterized by their shape and their degrees of freedom. Hinge and pivot joints are monaxial joints that only have one degree of freedom and thus allow only movements around one axis. Saddle, condyloid and plantar joints are biaxial joints with two degrees of freedom. Ball-and-socket joints are classified as triaxial joints that consequently allow movements around three axes.[19]

Joint movements are defined by the axis they rotate around. Movements around the sagittal-axis in the frontal plane are called ab-/adduction, movements around the transversal-axis in the sagittal-plane are called flexion/extension and rotations around the longitudinal-axis in the transverse plane are called inversion/eversion.(figure 2.2)

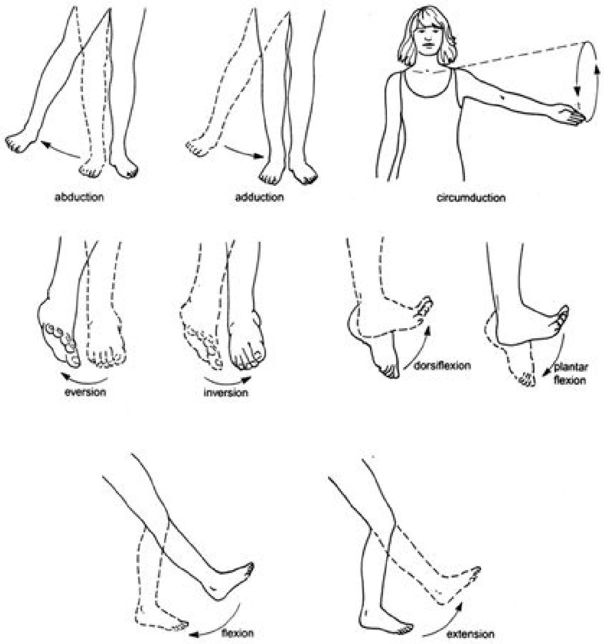

Figure 2.2: Movements of human joints[20]

2.2 Technical equipment, system setup and calibration

All records were made in the laboratory of Simi Reality Motion Systems GmbH in Unterschleissheim, Germany. The laboratory is equipped with different camera-systems. For this work the Basler scA640 - 120cg cameras, which acquire videos with a frame rate of up to 120 Hz and a resolution of 658x492 Pixels were utilized. All eight cameras are synchronized by a dedicated I/O box, which sends out a square wave signal for every frame that should be obtained. The I/O box is connected to the cameras with trigger cables, which also provide the power supply. Network cables are used to broadcast the videos live in the tracking software to control the acquisition.

Figure 2.3: Camera with ring lights[21]

Additionally, there are ring lights with 72 LEDs mounted on each camera (Fig.2.3). The LEDs are used together with retroreflective markers. These markers that are attached to the captured subject are illuminated by the ring lights and reflect the light so that they are visible as white spots in the videos. The white points are rudimentary for the marker-based tracking software. But before one can record movement videos, the system has to be calibrated. This is done with a so called T-Wand and a L-Frame (fig.2.4). The L-Frame is used to define the global 3D coordinate system. The long side of the L is determined as positive y-axis, which points along the direction of movement (fig.2.5). Therefore, the short side equals the positive x-axis. The z-axis is defined as perpendicular to the x- and y-axis applying a right-handed coordinate system. By moving the T-Wand within the tracking area to cover the volume of the measurement, the dynamic calibration data is obtained. The attached markers on the T-Wand have an exact known distance and are automatically tracked and assigned in the Motion software. Afterwards the software calculates the calibration data by using the tracked markers and the given distances between the wand markers.[21] To obtain a good calibration the T-Wand should cover the whole volume of the subsequent movement area. The user is given the ability to check the calibration parameters afterwards. The standard deviation of the detected wand length should be < 1.[21]

Figure 2.4: T-Wand and L-Frame [21]

2.3 Methods of motion tracking

There are different methods of motion tracking and therefore different software products that are developed by Simi. In this study only two products are used: the Simi Motion 3D for marker-based tracking (latest Version 9.2.1) and Simi Shape 3D for markerless tracking (latest version 2.2.1). In Simi Motion it is possible to obtain kinematic movement data by tracking markers. Simi Shape is an upgrade of Simi Motion. With this software it is possible to conduct markerless or hybrid motion tracking. In the following, these software applications and the methods of marker-based, markerless and hybrid movement analysis are explained.

2.3.1 Marker based tracking

The basis of marker tracking is the inverse dynamics calculations, which is used to gain the forces in the human body as well as the muscle moments of the joints. Therefore, the human body is divided in 16 segments (foot, shank, thigh, upper arm, forearm, hand, head, upper torso, lower torso and pelvis), which are linked by joints.[18] Orientation and location of the joints and the center of mass of each segments are defined by the marker 3D position. With the marker position as input, forces and joint moments can be calculated.[22] Furthermore, the markers are also used to define local segment coordinate systems, which have their origin in the particular center of mass (fig.2.5).[21]

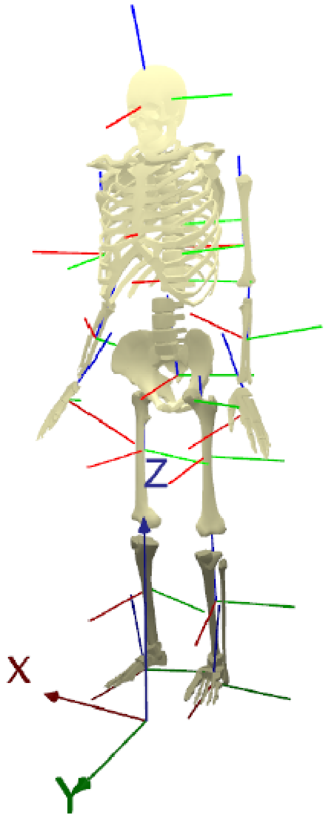

Figure 2.5: Local segment coordinate systems (red: x-axes, green: y-axes, blue: z-axes)[21]

The hip and shoulder joints are calculated in a complex way in comparison to ankle, knee, elbow and wrist joints.[23][24] They are defined by the connection line between the medial and lateral markers of the particular joints. ([21]p.365f)

According to the International Society of Biomechanics (ISB) standard [25][26][27], special joint coordinate systems are defined to describe joint rotations. Each joint consists of a proximal and a distal coordinate system, which are determined by four markers, building two vectors. The z-axis proceeds along the vector A (set up by marker one and two). The z-axis corresponds in the standard-configuration from distal to proximal. The cross product by vector A and B defines the x-axis, which points from dorsal to ventral (out of the desktop screen). The y-axis is calculated by the cross product between z- and x-axis and points horizontal from lateral to medial for the right body half and the other way around for the left half.[21] The joint angles are now described as rotations between the two joint coordinate systems. The rotation of the distal segment is calculated in the coordinate system of the proximal segment. Internally, they are given as rotation matrices and are then converted to x, y, z-Cardan angles for output data that can be easily interpreted. The first angle describes a rotation around the x-axis of the distal joint coordination system, followed by rotations around the y- and z-axes of the previously once respectivley twice rotated coordinate systems.([21]p.370-371, 374)

It is important that each marker is captured by at least two cameras at the same time to ensure the above mentioned assignment. Depending on the interest of the study, there are different marker models, according to which markers are assigned. In this study the full body marker set is used.[28]

2.3.2 Silhouette-based markerless tracking

The second tracking software used in this thesis is Simi Shape 3D. It enables motion capturing without using any markers. Simi Shapes tracking process relies on fitting a human body into a silhouette.
The execution of markerless tracking can be divided into three steps: segmentation, model initialization and tracking. First the calibration and setup work similar as for the marker tracking, but there is no need of ring lights as no markers have to be illuminated. The basis for a good markerless tracking is a good contrast between the subject and the background. This is maintained by the segmentation. The purpose of segmentation is to separate the recorded subject from the background in all camera images.[29] The first step that is conducted to get a segmented image is the so called background subtraction. Therefore, a recording of the empty room without the subject that is supposed to be analyzed is needed. The surrounding conditions (e.g. concerning equipment and lighting) have to be

the same as for the movement video. There is also the possibility to generate or edit a background frame in Shape, if there is no valid background video.[29] By subtracting the background and the motion images from each other (every pixel is compared concerning color and intensity and classified either as part of the background or as part of the analyzed subject), only the silhouette of the subject remains visible for each camera. Segmentation parameters can always be edited, if the background situation is more complicated. The next step is the initialization, where the model body is fitted in the human silhouette. Using the 2D silhouettes data from at least two cameras the 3D silhouette of the subject can be calculated. Hereby, the segment lengths and segment dimensions are adjusted to reality. The subsequent tracking process is thus performed with a model individually fitted to the actor.[29] Therefore, Shape uses an articulated model with a kinematic chain representing joints and corresponding segments. Each joint has its own degree of freedom and its parametrization. For instance, the root joint (3 translational and 3 rotational degrees of freedom), 5th lumbar vertebra, 7th cervical vertebra, shoulder joint, wrist joint, hip joint, ankle joint (all of them with 3 rotational degrees of freedom), skull base, elbow joint and knee joint (all of them with 1 rotational degree of freedom).[29] The lengths of the segments can be scaled (bone length) and the dimensions of the segments can be deformed. A mesh is attached to each segment such that the model is really 3-dimensional. The model underlies a rigid body assumption. This means that the lengths of the segments (distances between the joints) are fixed for the tracking process.([29]p.21) To ensure an authentic and quick alignment of the segments a initial static trial is performed before each motion capture. The so called psi-pose (figure 2.6) helps Shape to adjust the segments of the model automatically, which is recommended but not mandatory.[29]

If the model is aligned satisfactionally the tracking can be started. For tracking, an interative closes point (ICP) algorithm is used to adjust the pose of the model to the actual pose of the 3D silhouette for each frame by looking for correspondences between the silhouette and the model. ([29]p.69)

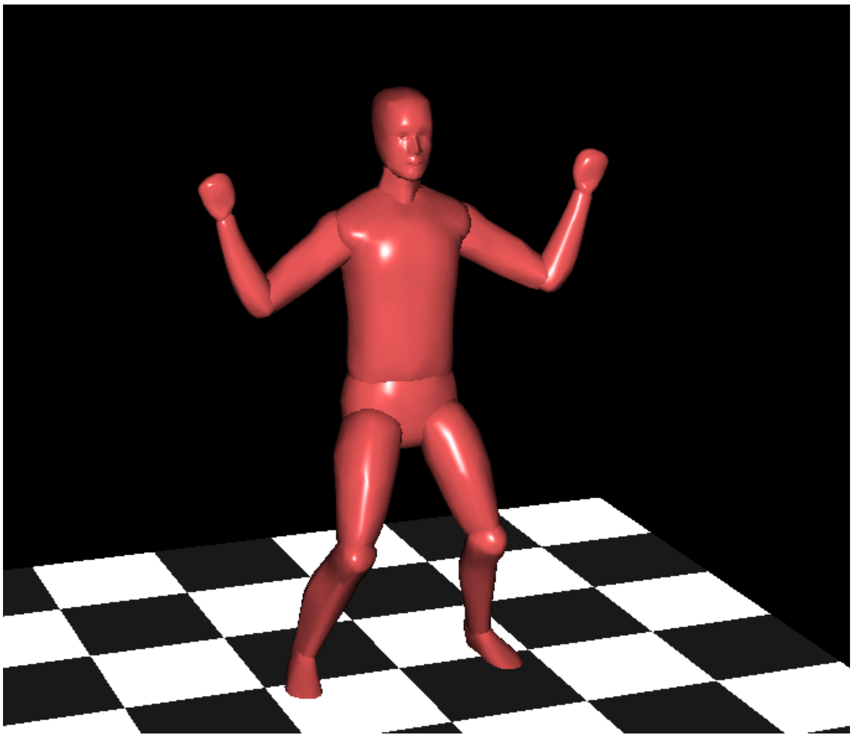

Figure 2.6: Psi-Pose to adjust model segments

2.3.3 Hybrid tracking with Simi Shape

Hybrid tracking is a combination of at least two tracking systems. In this case silhouette tracking (Shape) is combined with markers. The procedure remains the same as for markerless tracking, but 3D marker data is additionally implemented in the tracking process. Therefore, the markers that are used have to be tracked previously with Simi Motion. There are two possibilities to implement markers: 2D marker coordinates or 3D marker coordinates. For using the 3D coordinates the markers have to be assign and furthermore, 3D data has to be calculated, which can be exported easily. The 2D marker coordinates only need to be assigned in Motion and have to be saved as a special .xml-file. Important settings for the hybrid tracking are the 'weight of marker-' and 'weight of silhouette-correspondences'. By changing these parameters the user can define from which data the model is taking its position from ([29]p.70f).

If the weight for silhouette-correspondences is set to low, segments that are not unambiguously defined by three markers may lose correspondences with the silhouette. This could happen if equally weighted silhouette- and marker-correspondences are used and can lead to falling apart of the model. Setting the silhouette correspondences 20-fold higher than for marker correspondences has been proved to deliver stable tracking results.[18]

2.4 Return to Sport screening

The return to sport screening is an evaluation method to obtain the status of biomechanical readiness of an athlete to return to sport or physical activity after an injury or surgery. Basically, the athlete performs different movements, including lateral movements, jumping, cutting, etc., to assess muscle strength, balancing and running symmetry. According to the outcome the physical therapist develops a personal practice schedule for the athlete to overcome his deficits. Most of the screenings aim at the probability of re-injury, therefore most of the clinicians choose their own combination of movements.[1] There are a few publications [30][31][2][32] which show that limited movement patterns in simple dynamic movements, such as landing or cutting tasks, increase the force and moments in the knee joint, which may lead to a higher injury-risk of the anterior cruciate ligament (ACL) based on biomechanics. Females with a larger initial hip flexion and internal rotation were associated with a larger peak knee valgus moment. They also show that by changing the movement patterns the risks of injury decrease. For example, the load in the knee decreases if the hip and the knee flexion in the sagittal plane increases.[33][34] The Functional Movement Screening (FMS), developed by Cook et al.[35] is an example for a test battery trying to combine seven of those movements. Each movement is evaluated and scored by its execution and the whole test score is calculated by adding up the single scores. There are publications which show [36], that most of the screening batteries like the FMS correlate with a higher risk of re-injury, when failing test batteries. But these tests are all based on subjective analysis. Furthermore, each test battery has its own score and is not comparable to others. There is no standardization besides the movements, which makes it difficult to compare these tests in the final step.

For this work the screening battery of Dr. Christopher M. Powers serves as guideline for the markerless approach. Dr. Powers is the founder and owner of the Movement Performance Institute (MPI) in Los Angeles. In addition, he is a Professor in the Department of Biokinesiology & Physical Therapy, and Co-Director of the Musculoskeletal Biomechanics Laboratory at the University of Southern California. Furthermore, he has a Ph.D. in Biokinesiology and published over 150 research articles.[37] He is also considered one of the world's leading authorities on knee injuries, including the tear of the anterior cruciate ligament. According the return to sports question he has developed a six movement screening, which results in a total score to come to a conclusion about the readiness of the athlete. The test differs from the FMS, because Dr. Powers only examines the movement patterns of the lower body and the trunk movement during high dynamic movements. Therefore, it is focused on the examination of ACL reconstruction patients, who are trying to return to sport. His return to sport screening was developed in the United States and is considered to be the a good return to sport tool that evaluates the quality of movement. Approximately 150 physical therapists have been trained to perform the return to sport screening and approximately 1000 physical therapists have been exposed to the test.[1] In this work the MPI return to sport screening is not evaluated by itself. It provides only the basis for the evaluation of markerless tracking for the usage in the clinical field.

[1] Mail exchange with C.M. Powers

3 Materials and methods

This chapter will present the methodical approach of this work. First, the main goal of this work is summed up and presented as hypotheses. Then the return to sport movements will be described, followed by the tracking process, the calculation templates to calculate the required data for the analysis and at last the statistical analysis, which is needed to compare the results with each other.

3.1 Hypotheses for the evaluation

The main goal in this work focuses on the application of markerless silhouette-based tracking as alternative to the, on one hand expensive and time consuming marker-based tracking and on the other hand the simple but subjective rater-based inspection. First the rater-based screening is compared to the gold standard, the marker-based 3D-Motion tracking. As mentioned in the introduction rater-based screenings are the most common method to perform return to sport screenings in the clinical environment. The reliability is not yet proven as consistent. This leads to the first hypothesis in this work:

Hypothesis 1 (H1): The inter-rater-reliability of a rater-based screening does not deliver good results.

Marker-based motion tracking has no use in the clinical daily routine, because of its time consuming and expensive implementation. Therefore, it is only used as the reference for the other evaluation methods in this work. Both the rater-based and the markerless tracking are evaluated to the marker-based tracking, according measured angles and scoring. This investigation serves the purpose to classify markerless tracking in the field of return to sport screenings for clinical application and to show the advantages a markerless silhouette-based tracking system brings along. Before this question can be answered, the rater-based method has to align itself with the gold standard, to make sure where markerless tracking can be sorted in between these two "standards".

Hypothesis 2 (H2): Rater-based screenings deliver less accurate results than marker-based tracking for a return to sport screening.

According to previous works [18][15][38], the markerless tracking should be able to produce results, which come close to the accuracy of marker-based tracking and therefore H3 is phrased as followed:

Hypothesis 3 (H3): Markerless silhouette-based tracking delivers as accurate results as marker-based tracking, when it comes to return to sport screenings.

These hypothesis lead to the main investigation in this work:

Hypothesis 4 (H4): Markerless tracking is, when compared to a rater-based inspection, a more objective and accurate method to investigate return to sport screenings.

It is important to note, that the introduced return to sport screening is not evaluated as a return to sport screening itself. It only serves as a guideline for the evaluation of markerless tracking as a reliable and objective method for clinical application.

3.2 Subjects

Eight average male athletes participating in cutting and jumping sports were recruited for this thesis. The average age of the subjects is 26 ± 1.8 years and the average height and weight are $1.89m \pm 7cm$ and $84kg \pm 11.28kg$. The participants have an average of 15 years of experience in football, volleyball and basketball. Not one of them has had a serious injury in the previous five years.

3.3 Return to Sport movements

In the field of return to sport there is a big variety of movements, which are considered to be highly diagnostic. The following six movements are commonly used for rehabilitation, risk of injury evaluation and performance testing of healthy and injured athletes.[1] All of these movements are categorized by six criteria like Hip Stability, Pelvic Drop, Trunk Stability, Shock Absorption, and Hip Strategy, which is derived from Trunk Lean, Thigh Angle and Tibia Position. The categorizations in this chapter are extracts out of the handouts from the master class of Dr. Powers.

Not all of the criteria apply to each movement, therefore, the single criteria are explained and assigned to the return to sport movements, in the following.

3.3.1 Step Down: movement, parameters and score definition

The Step down is the first of the six movements. The subject stands with one food on a small box (20 cm high) the other extended forward approximately 20° and is instructed to touch the ground with the heel of the extended foot by bending the weight bearing knee. The weight bearing foot is supposed to keep steady on the box without lifting the heel. Every subject performs this movement three times with his strong leg and three times with his weak one.

All movements are analyzed with different criteria, as mentioned above. In Table 3.1 the criteria to score the Step Down are shown. Table 3.2 is the categorization for the Hip

Strategy in table 3.1.

Table 3.1: Criteria for Step Down

Criteria	Categorization	Definition	Score
Hip Stability	No knee valgus	-	2
	Mild knee valgus	vertical line from knee joint center hits ankle joint center or lateral	1
	Significant knee valgus	vertical line from knee joint center hits medial to ankle joint center	0
Pelvis Stability	No Pelvic drop/rise	drop/rise 5° or less	2
	Mild pelvic drop/rise	drop/rise 6° to 10°	1
	Significant drop/rise	drop/rise greater than 10°	0
Trunk Stability	No trunk lean	trunk lean 5° or less in any direction	2
	Mild trunk lean	trunk lean 6° to 10° in any direction	1
	Significant trunk lean	trunk lean greater 10°	0
Hip Strategy	Significant hip strategy	trunk + thigh = 2	2
	Mild hip strategy	trunk + thigh= 1	1
	No hip strategy	trunk + thigh = 0	0

Table 3.2: Hip Strategy for Step Down

Criteria	Categorization	Score
Trunk	trunk angle 30° or more	1
	trunk angle less than 30°	0
Thigh	thigh angle 45° or less	1
	thigh angle greater than 45°	0

3.3.2 Drop Jump: movement, parameters and score definition

The subject stands with his feet, shoulder width apart, on a chair (50 cm high) and is instructed to drop off the chair forward, land with the experimental foot on the force plate, the other foot on the ground, absorbing the drop as quick as possible and counter jump to a maximum height by reaching both arms up. Each subject is constrained to perform a jump as high as possible. Therefore, each one can decide how low they are reaching after the drop. Furthermore, the following jump should be directed slightly forward. Table 3.3 shows different criteria than for the Step Down.

Table 3.3: Criteria for Drop Jump

Criteria	Categorization	Definition	Score
Hip Stability	No knee valgus	-	2
	Mild knee valgus	vertical line from knee joint center hits ankle joint center or lateral	1
	Significant knee valgus	vertical line from knee joint center hits medial to ankle joint center	0
Shock Absportion	Significant Shock Absorption	thigh angle 30° or less	2
	Mild shock absorption	thigh angle 31° to 45°	1
	No shock absorption	thigh angle greater than 45°	0
Hip Strategy	Significant hip strategy	trunk + thigh + tibia = 3	2
	Mild hip strategy	trunk + thigh + tibia = 2	1
	No hip strategy	trunk + thigh + tibia = 1	0

Table 3.4: Hip Strategy for Drop Jump

Criteria	Categorization	Score
Trunk	trunk angle 30° or more	1
	trunk angle less than 30°	0
Thigh	thigh angle 45° or less	1
	thigh angle greater than 45°	0
Knee	vertical line from knee joint center hits toes	1
	vertical line from knee joint center hits anterior to toes	0

3.3.3 Deceleration: movement, parameters and score definition

For the Deceleration, the subject is supposed to run quickly forward to the force plate and stop the movement by pushing with the experimental food on the plate and initiate a counter movement backwards for at least three steps. All subjects are instructed to remain preferably short on the force plate to ensure a quick execution. To perform a mostly natural and comfortable execution every subject has at least three trials.

Table 3.5: Criteria for Triple Jump

Criteria	Categorization	Definition	Score
Hip Stability	No knee valgus	-	2
	Mild knee valgus	vertical line from knee joint center hits ankle joint center or lateral	1
	Significant knee valgus	vertical line from knee joint center hits medial to ankle joint center	0
Pelvis Stability	No Pelvic drop/rise	drop/rise 5° or less	2
	Mild pelvic drop/rise	drop/rise 6° to 10°	1
	Significant drop/rise	drop/rise greater than 10°	0
Trunk Stability	No trunk lean	trunk lean 5° or less in any direction	2
	Mild trunk lean	trunk lean 6° to 10° in any direction	1
	Significant trunk lean	trunk lean greater 10°	0
Shock Absportion	Significant Shock Absorption	thigh angle 30° or less	2
	Mild shock absorption	thigh angle 31° to 45°	1
	No shock absorption	thigh angle greater than 45°	0
Hip Strategy	Significant hip strategy	trunk + thigh + tibia = 3	2
	Mild hip strategy	trunk + thigh + tibia = 2	1
	No hip strategy	trunk + thigh + tibia = 1	0

Table 3.6: Hip Strategy for Triple Jump and Deceleration

Criteria	Categorization	Score
Trunk	trunk angle 30° or more	1
	trunk angle less than 30°	0
Thigh	thigh angle 45° or less	1
	thigh angle greater than 45°	0
Tibia	vertical line from knee joint center hits anterior to ankle joint center	1
	vertical line from knee joint center hits ankle joint center or posterior	0

3.3.4 Triple Jump: movement, parameters and score definition

The aim of this test is to control and stabilize the body after landing the third jump. From about 3-5 meters the subject starts jumping continuously on one leg, the experimental leg. He is instructed to land with his third jump on the force plate and hold this position for at least two seconds before stepping of the plate. Every subject has again three trials, which are all recorded to allow to choose the most accurate one after testing. The analyzed criteria is the same as for Deceleration. See table 3.5 and 3.6.

3.3.5 Side-Step-Cut: movement, parameters and score definition

The Side-Step-Cut is an important movement because of the change of direction from the line of movement to a perpendicular movement. The subject is instructed to run quickly towards the force plate and change direction on the force plate with the experimental food. Ideally the change of direction is in 90 degrees to the movement direction.

Table 3.7: Criteria for Side-Step-Cut

Criteria	Categorization	Definition	Score
Hip Stability	No knee valgus	-	2
	Mild knee valgus	diagonal line from ankle joint center to knee joint center hits umbilicus or medial	1
	Significant knee valgus	diagonal line from ankle joint center to knee joint center hits lateral to umbilicus	0
Pelvis Stability	No Pelvic drop/rise	drop/rise 5° or less	2
	Mild pelvic drop/rise	drop/rise 6° to 10°	1
	Significant drop/rise	drop/rise greater than 10°	0
Trunk Stability	No trunk lean	trunk lean 5° or less in any direction	2
	Mild trunk lean	trunk lean 6° to 10° in any direction	1
	Significant trunk lean	trunk lean greater 10°	0
Shock Absportion	Significant Shock Absorption	thigh angle 30° or less	2
	Mild shock absorption	thigh angle 31° to 45°	1
	No shock absorption	thigh angle greater than 45°	0
Hip Strategy	Significant hip strategy	trunk + thigh + tibia = 3	2
	Mild hip strategy	trunk + thigh + tibia = 2	1
	No hip strategy	trunk + thigh + tibia = 1	0

Table 3.8: Hip Strategy for Side-Step-Cut

Criteria	Categorization	Score
Trunk	trunk angle 30° or more	1
	trunk angle less than 30°	0
Thigh	thigh angle 45° or less	1
	thigh angle greater than 45°	0
Tibia	vertical line from knee joint center hits anterior to ankle joint center	1
	vertical line from knee joint center hits ankle joint center or posterior	0

3.3.6 Lateral Shuffle: movement, parameters and score definition

The subject faces sideways to the walkway and performs quick side steps until he reaches the force plate, where he stops the movement and accelerates in the opposite direction for 2-4 meters. This movement is repeated three times continuously without hesitation to guarantee a perfect hit on the plate. Furthermore, the subject is constrained to rest as briefly as possible on the force plate to ensure a quick execution.

Table 3.9: Criteria for Lateral Shuffle

Criteria	Categorization	Definition	Score
	No knee valgus	-	2
Hip Stability	Mild knee valgus	diagonal line from ankle joint center to knee joint center hits umbilicus or medial	1
	Significant knee valgus	diagonal line from ankle joint center to knee joint center hits lateral to umbilicus	0
Trunk Stability	No trunk lean	trunk lean 5° or less in any direction	2
	Mild trunk lean	trunk lean 6° to 10° in any direction	1
	Significant trunk lean	trunk lean greater 10°	0
Hip Strategy	Significant hip strategy	trunk + thigh + tibia = 3	2
	Mild hip strategy	trunk + thigh + tibia = 2	1
	No hip strategy	trunk + thigh + tibia = 1	0

Table 3.10: Hip Strategy for Lateral Shuffle

Criteria	Categorization	Score
Trunk	trunk angle 30° or more	1
	trunk angle less than 30°	0
Thigh	thigh angle 45° or less	1
	thigh angle greater than 45°	0
Knee	vertical line from knee joint center hits toes	1
	vertical line from knee joint center hits anterior to toes	0

3.3.7 Final score

The final score is obtained by adding up all six single scores. Using this final score, the physical therapists should come to a conclusion about the biomechanical readiness of the athlete. A total score below 39 means a failing of the test. The range 40 until 44 points is the borderline and a scoring between 45-50 means passing the return to sports screening.

3.4 Tracking process

For the process of marker-based and markerless tracking, the tracking software Simi Motion and Simi Shape are used. Both software packages are provided by Simi Reality Motion Systems. The tracking is performed separately. The 2D-tracking is performed by professionals who have been working with Dr. Christopher Powers for years now. Because the 2D-screening works with single images, it only allows to estimate a certain point of time. The lowest point of the center of mass (COM) is considered to be the perfect moment.(Appendix B.1) The COM was determined with Simi Shape under application of the Hanavan Model [39]. It is to say, that the Hanavan Model is usually used for marker-based tracking, but it has been proven, that the usage of this model in Shape results only in an vertical offset.[38]

3.4.1 Rater-based evaluation

According to the Simi laboratory setup, only two cameras are used for the rater-based evaluation, one for the sagittal and one for the frontal view. The scoring is then performed by visual inspection at the desktop screen of the computer. Most of the time goniometers are used on phones to measure the angles, as mentioned earlier in Chapter 3.2. Therefore, the images are enlarged and the phone is hold on to the screen.

The raters, asked for this task, are professionals and have an experience of approximately 2-4 years with this *MPI* return to sport screening. Before the rater-based evaluation is performed the images have to be edited and the markers removed, otherwise the scorer are tempted to use the markers on the anatomical landmarks as leading points for the angle measurements. But not every marker is removed, only the important ones such as:

- trochantor major (left and right)
- spina iliaca anterior superior right
- spina iliaca anterior superior left
- condylus lateralis (left and right)
- manubirium sterni
- Processus xiphoideus
- acromion (left and right)
- thigh (left and right)

The Pictures 3.1 and 3.2 show an example of the image before and after the markers are removed:

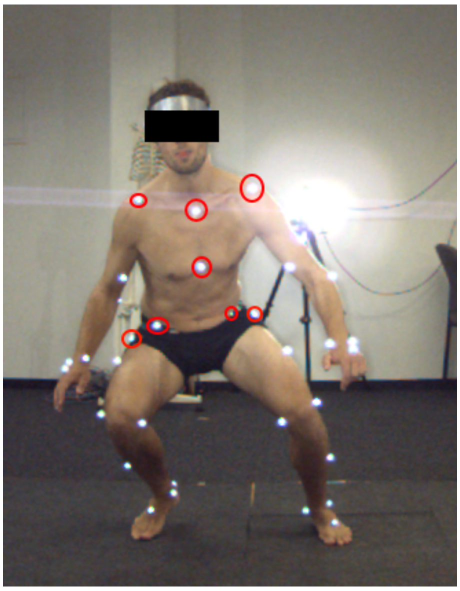

Figure 3.1: Subject with important markers before they are removed (red circles)

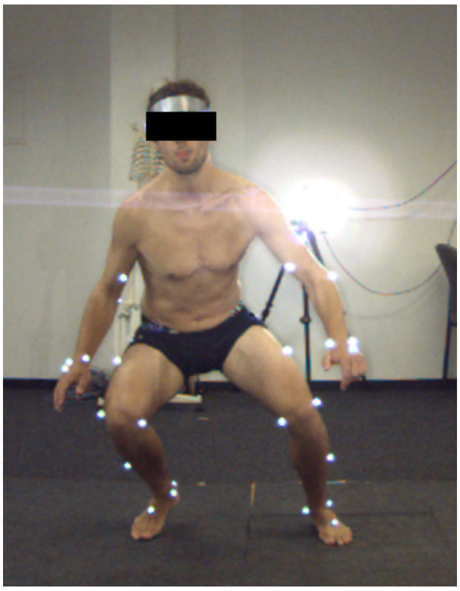

Figure 3.2: Subject without the important markers

All images for one subject are put together into a protocol and are uploaded to "Google Drive" (Google Inc., Mountain View, USA) and "Dropbox" (Dropbox Inc., San Francisco, USA), where the chosen raters have access to download, rate and upload the files again.

Five raters have replied and scored the eight subjects. Out of these five data sets the mean and the standard deviation are calculated to come on a common base for the comparison. In all statistical approach the mean value of the five raters is used to represent the observer-rating.

3.4.2 System based evaluation

3.4.2.1 Setup and Calibration

The movements are recorded in the laboratory of Simi Reality Motion Systems. It is equipped with eight 0.3 megapixel cameras and a walkway in which a force plate from Kistler is embedded. The frame rate of the cameras is set to 100 Hz and the force plate uses 1000 Hz for data acquisition. Four of these cameras are placed with tri-pods and clams on the floor or the wall in hip-height (camera 1-4), two each sagittal and frontal or dorsal respectively. The additional four cameras are placed in the room corners and hang to the roof (camera 5-8), filming from above (figure 3.3). This setup guarantees that every marker and body segment can be seen at any time of recording in at least two cameras. Also, all cameras are either zoomed in or close enough to capture as little surrounding area as possible. This guarantees a better differentiation of the arms and legs for the markerless tracking.

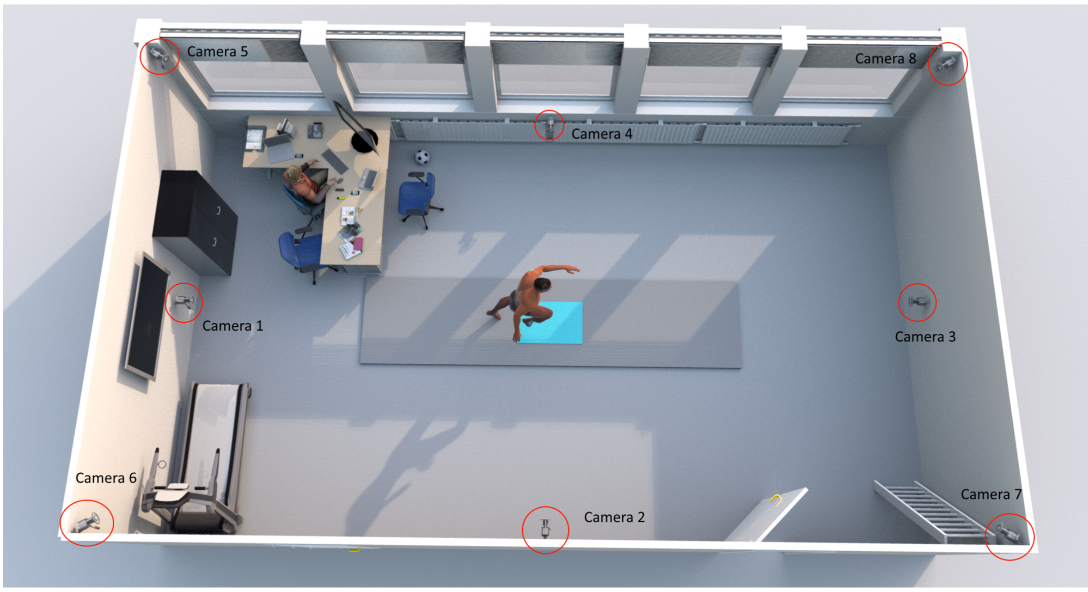

Figure 3.3: Top view of the Simi Lab

As figure 3.4 shows the cameras are connected with the computer via Ethernet cable (GigE) for the data transfer. Additionally a trigger cable from each camera is connected to the I/O-Box, which guarantees energy supply and the synchronization of all videos. Furthermore, the force plate is also connected to the I/O-Box.

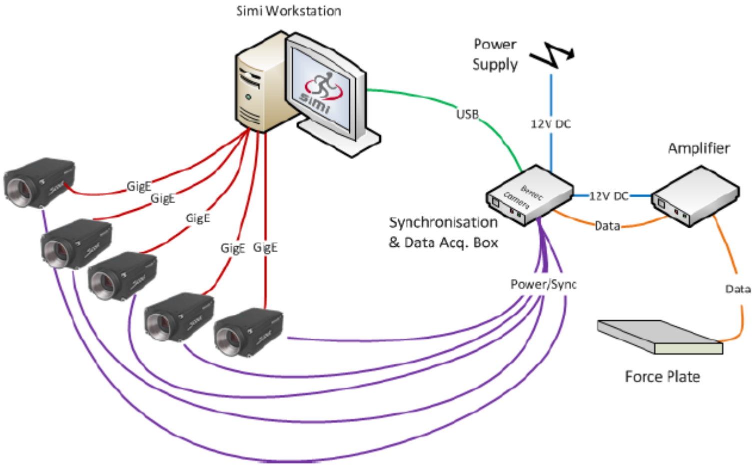

Figure 3.4: schematic setup for a 5-camera-system with integrated force plate

All recordings use the same calibration to distort the cameras and define the coordinate system. The L-frame, mentioned in Chapter 2 is placed in the lower right corner of the force plate. The T-wand is used to perform the so-called "wand dance" to cover the capturing volume.([21] p.129-132) Therefore, a person must capture approximately 40 seconds of video while waving the wand around the tracking area. Afterwards, the calibration is calculated and the standard deviation in this case was 1.26mm , which is a very good result. The calibration can now be imported in every project, as long as the cameras are not moved.

The obtained data is not filtered, due to the fact that the exact position of the joints and body segments are needed.

3.4.2.2 Marker-based tracking with Simi Motion

As mentioned earlier, the full body marker set is used in this setup. Picture 3.5 shows the position of all 45 markers. All subjects wear only tights and the markers are directly attached to the skin to minimize movement artifacts of the skin.

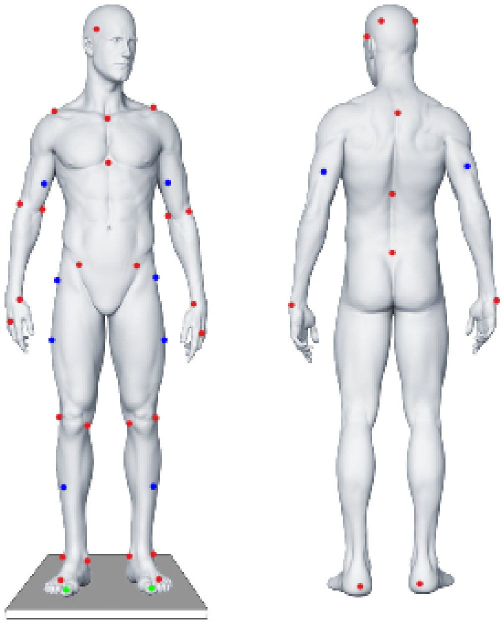

Figure 3.5: Marker Set for the inverse kinematics

When the markers are attached according to the model, first a static trial is recorded. The subject stands in an upright position with the arms hanging straight besides the body and the palms point forward. This pose is used to calculate the person-specific data such as length of body segments and location of joint axes. Afterwards, the dynamic trial is performed, containing the movements which are supposed to be analyzed. After the recording one initialization frame is needed in which each marker is assigned correctly in at least two cameras. This is done manually. The assignment for the rest of the recording is done automatically using the initialization frame and the implemented marker set. In the final step the inverse dynamics are calculated by using the force plate data and the 3D-marker data.

3.4.2.3 Markerless tracking with Shape

For the markerless tracking with Shape there has to be either an empty video with only the background or at least one frame without showing the subject to perform the background subtraction. In this case an empty video of the laboratory is captured before each movement, because the setup for drop jump and step down changes with the usage of the needed box and chair, respectively. Both videos, the empty and the movement video, have to be adjusted to the same image processing settings, otherwise the background subtraction will not work properly. After the settings are adjusted, the Simi project file is uploaded in Simi Shape. Usually the subject adopts the psi-pose, as it is described in Chapter 2.3.2, to adjust the model to the subject's body proportions, but there is also the possibility to do the fitting manually. In this case it is easier to fit the model manually, because the tracked sequence is short and the model can be adjusted perfectly in the exact moment where it needs to fit the best. Nevertheless, after the model is scaled and adjusted to the body of the subject, the tracking process is started. Approximately one second forward and backward from the lowest point of COM is tracked to cover the important part of the movement. During the tracking process the model sometimes moves out of the silhouette and has to be fitted in again. Picture 3.6 shows an almost perfect background subtraction and model fitting.

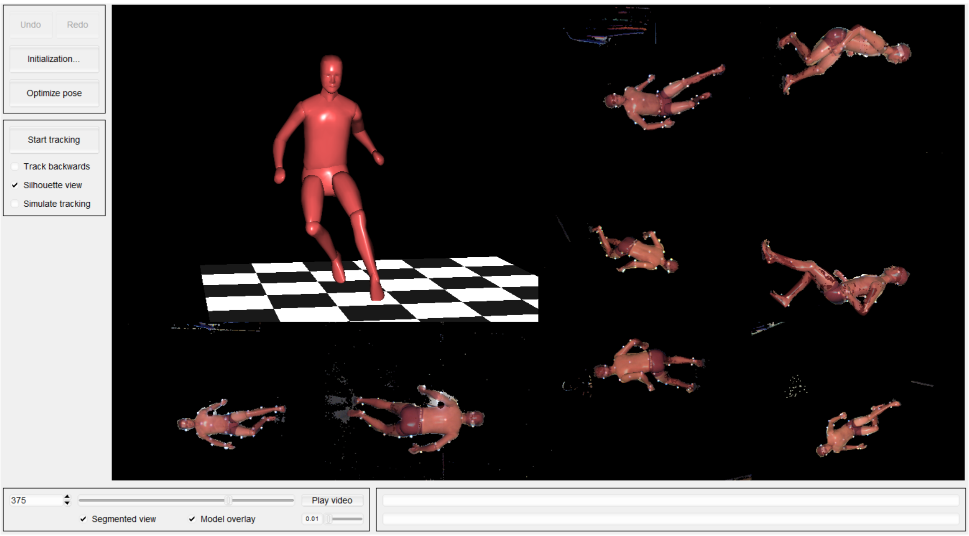

Figure 3.6: Example of a good background subtraction and model fitting in Shape in all eight cameras

Is the tracking completed and saved, the 3D-motion data is imported in the project file and the inverse dynamics are calculated automatically.

3.4.2.4 Hybrid tracking with Simi Shape

As mentioned earlier Hybrid tracking is a combination of marker-based and markerless tracking. The silhouette of the subject is combined with the special defined markers to improve the performance of markerless tracking. In this case the focus is laid on the three hip markers *mid spina iliaca superior posterior* and *anterior superior iliac spine* left and right. These three markers define the pelvis and its movement. First of all the markers have to be tracked, which is already done by the marker-based analysis. The 3D-marker data has to be imported in the Simi Motion file, which is used for the markerless tracking. Afterwards Shape is launched with the specific Shape settings, such as background subtraction and model information. This ensures that the segments of the subject model remain the same, so that there is no deviation compared to the markerless tracking. Additionally it simplifies the tracking process. In the Shape settings the three hip marker have to be activated and the 3D-data has to be selected. With checking the *Use 3D Marker correspondences* in the *Tracking Parameter* settings the tracking process can be started. Figure 3.7 shows the hybrid tracking of a subject with the three hip markers (yellow dots).

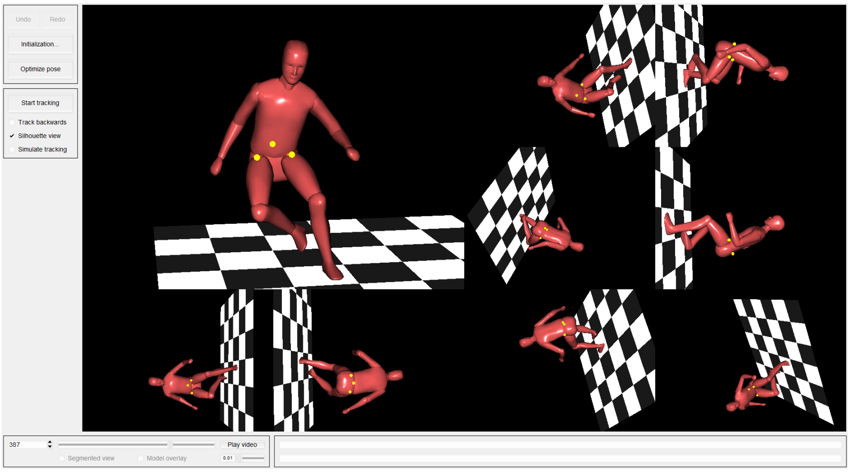

Figure 3.7: Shape Workspace for Hybrid tracking with three activated hip marker

3.5 Methods to calculate the score in system based evaluation

Simi Motion offers a lot of data either from marker-based or markerless tracking, e.g. segment centers, joint centers, joint angles, center of gravity etc.

But regarding the data acquisition for return to sport movements Motion does not offer the exact information about angles or positions defined by Dr. Powers. On the other hand Motion offers a huge variety on calculations and data processing tools. With these tools the further comparison of 2D-rater-based data and 3D data can be achieved. Therefore, the criteria, which are mentioned in Chapter 3.3 are calculated with the provided tools.

Motion works with .smt-files as calculation templates, which are written and edited in XML-coding language. To simplify and to speed up the data acquisition after the tracking process, templates are created and saved for further application.

Furthermore, the folder structure in Simi Motion is important, which is different between the marker-based tracked and markerless tracked projects. Therefore, different calculation templates for each tracking method need to be created. Also, a discrimination has to be done between left and right limb. At the end, four different templates need to be created to achieve an almost fully automatized analysis.

3.5.1 Hip Stability - marker-based, markerless and hybrid

The Hip Stability criteria is in the 2D-evaluation only accessible by drawing a virtual vertical line from the knee joint center to evaluate whether the line hits lateral or medial to the ankle joint center. Therefore, there is no quantitative evidence possible only a yes or no. In the Simi Motion data processing feature a calculation giving the distance in any of the three directions (X,Y,Z) is available. For the movement in the frontal plane the direction in X is the first choice. This works fine for all movements besides Side-Step and Lateral Shuffle. These two have a different categorization, mentioned in Chapter 3.3.5. According to this the calculation is way more complex. Assumed that the umbilicus is approximately the center of mass of the body, the COM, the knee joint center and the ankle joint center getting split into the single coordinates (x,y,z). The y-coordinate is set to zero to create 2D-coordinates for each joint center. Now two vectors, one from ankle joint center to the COM ($\vec{v}$) and one to the knee joint center ($\vec{w}$), are created and the cross product is calculated. Because of the fact that the cross product generates a vector whose absolute value is equivalent to the surface area of the parallelogram (with the sides v and w) and who in addition stands on the parallelogram and therefore matches the Y-coordinate, the Y-coordinate can be divided by the normalized vector $\vec{v}$. In equation 1 the normalized cross product is used, but this would only obtain the absolute value. Therefore, the Y-coordinate of the cross product (equation 2) is used, which results now in the distance d from the knee to the vector $\vec{v}$ through the COM.[40]

$$d = \frac{|\vec{a}x(r\vec{Q} - r\vec{1})|}{r\vec{1}} \tag{1}$$

$$d = \frac{\vec{v} \times \vec{w}}{|\vec{v}|} \tag{2}$$

Out of the distance of the vector to the knee a statement, whether the knee vector runs medial (score of 1) or lateral (score of 0) to the center of mass is given. A two is given, if there is obviously no knee valgus. Because this criteria delivers only a qualitative statement, the categorization for a quantitative value can be freely chosen. Therefore, a change of distance by at least $2.5cm$ of the vector leads to a change in the visual interpretation. Furthermore, $5cm$ are enough to shift the knee from a complete valgus to a varus position. Following this every result lower than $< -0.025m$ is scored as a 2, values between $0.025m$ and $0m$ are scored as 1 and positive values are noted as a 0, because this would indicate a significant knee valgus. This categorization applies only for the right leg. For subjects using the left leg the algebraic sign is switched, because the definition of varus und valgus switches.

3.5.2 Pelvis Stability - marker-based, markerless and hybrid

According to the tables of chapter 3.3 the Pelvic Stability calculation is based on the movement of the left and right hip joint center in the frontal plane. Therefore, the option "angle with XY-plane" is selected.

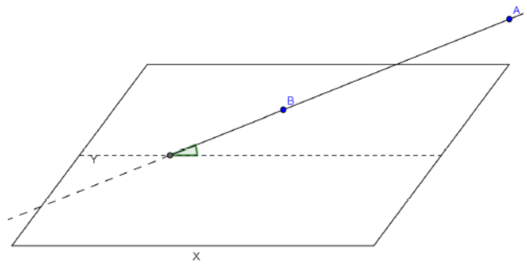

Figure 3.8: Angle with XY-Plane[21]

3.5.3 Trunk Stability - marker-based, markerless and hybrid

The segment center of the pelvis and the thorax are used for the Trunk Stability. They are set up with YZ-plane to generate an angle in the frontal plane.

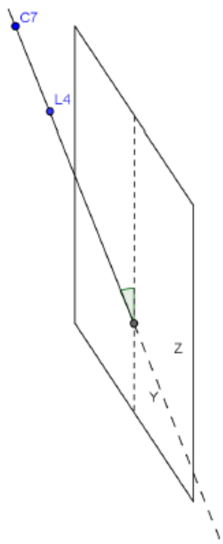

Figure 3.9: Angle with YZ-Plane[21]

3.5.4 Shock Absorption - marker-based, markerless and hybrid

To generate the angle of the thigh to the horizontal plane, an angle between the XY-plane and a connection line from hip joint center to knee joint center is induced. (Figure 3.8)

3.5.5 Hip Strategy - marker-based, markerless and hybrid

The Hip Strategy consists of two respectively three parameters as mentioned earlier.

Trunk Angle - marker-based, markerless and hybrid

The Trunk Angle is the movement of the trunk in the sagittal plane, which can be quantified by calculating the angle of the connection line from shoulder joint center to the hip joint center on the right or left side and the XZ-plane.

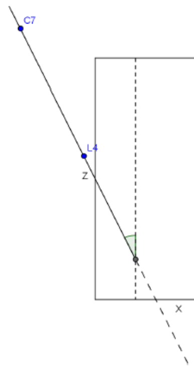

Figure 3.10: Angle with XZ-Plane[21]

Thigh Angle - marker-based, markerless and hybrid

The Thigh Angle is the same as the Shock Absorption (See Chapter 3.5.4).

Tibia/Knee Position - marker-based, markerless and hybrid

The Tibia/Knee Position criteria is as well as the Hip Stability in the 2D-evaluation only accessible by drawing a virtual vertical line from the knee joint center to evaluate whether the line hits the ankle joint center or posterior. In case of the Drop Jump and the Lateral Shuffle the knee position is according to the position of the toes. Therefore, the data processing feature "Distance in Y-Direction" is chosen, as well as the variables knee joint center and ankle joint center or for the knee position the marker on the metatarsal II-III.

3.5.6 XML-programmed templates

Each calculation has to be created, executed and saved manually, before it is possible to merge them all together. All the files have the same structure and the only thing which has to be edited are the connections of each data group to ensure all tracks (0=x, 1=y, 2=z) are linked (listing 1). Additionally the calculation counter in the head has to be updated too.

```
<Operation ID="Op001">
      <Name>KSP neu</Name>
      <Magic>1IN3</Magic>
      <LinkName>Intern</LinkName>
      <Track>0</Track>
      <Param N="1">
        <Name>data</Name>
        <Type>IMPORT</Type>
        <ID>Imp001</ID>
      </Param>
    </Operation>
    <Operation ID="Op002">
      <Name>KSP neu</Name>
      <Magic>1IN3</Magic>
      <LinkName>Intern</LinkName>
      <TrackLink>Op001</TrackLink>
      <Track>1</Track>
      <Param N="1">
        <Name>data</Name>
        <Type>IMPORT</Type>
        <ID>Imp002</ID>
      </Param>
    </Operation>
    <Operation ID="Op003">
      <Name>KSP neu</Name>
      <Magic>1IN3</Magic>
      <LinkName>Intern</LinkName>
      <TrackLink>Op001</TrackLink>
      <Track>2</Track>
      <Param N="1">
        <Name>data</Name>
        <Type>IMPORT</Type>
        <ID>Imp003</ID>
      </Param>
    </Operation>
```

Listing 1: Single Tracks of the new COM are merged together

The templates are supposed to run independently after activation, therefore, the folder structure needs to be same throughout all project files, otherwise the data groups are not found by their index. So after implementing all single files into one, the index of the groups are checked and edited.

3.6 Statistics

Before the actual comparison of rater-based, markerless, hybrid and marker-based tracking is performed, the inter-rater-reliability (IRR) is analyzed with the Inter-class-correlation coefficient (ICC). The ICC is a commonly-used statistics for assessing inter-rater-reliability for nominal, ordinal, interval variables and it suits for studies with multiple raters. The ICC is divided into several variations based on the nature of the current study. Therefore, four major factors determine which variation is best to choose. First, the raters in this work are not selected randomly, therefore the so-called "two-way" variation applies. Second, the inter-rater-reliability should be characterized by the absolute agreement. That means it is important for the study that the values from the angles are all similar. Third, the reliability of the ratings has to be quantified, either based on average of multiple raters or based on ratings of one single rater. In this work the average of all raters is used for further testings and so the based on average variation is selected. As a last step the mixed effects model is chosen. This implements that the raters are considered to be fixed and the researcher does not want to generalize the results to a larger population.[41]

To get a clue of whether the 2D rating and the markerless 3D tracking are as effective as the gold standard the measured angles from chapter 3.2 are compared within each criteria. First of all the 2D-rater-based data is compared with the 3D-Motion data and then the markerless tracking is compared. For the means of data comparison, a special statistic method has to be used in this work. The fact that only a single point of time is analyzed makes it difficult to find the right statistic method. An easy correlation coefficient would not work. A paired t-test or a Wilcoxon signed-rank test, depending on the normal distribution, is no option either. Both tests are comparative tests and try to prove whether the means of both variables are significantly different from each other. If this is not the case and the alternative hypothesis is rejected at alpha-level of 0.05, one cannot claim that both are the same. There is not enough evidence to prove that, therefore, it is only an assumption.[42]

In this case the tool of choice would be an equivalence test or a two one-sided t-test (TOST). The aim is to determine a margin ($\pm\delta$), where the means can be considered equivalent.[42][43] The one-sided tests use the interval limits as reference value, to which the difference has to be proven as significant. Therefore, one is tested from left, lower equivalence limit(LEL) of the margin of equivalence and the other one from right, the upper limit of equivalence (UEL). If the alternative hypotheses, that there is a significant difference, of each one-sided test are rejected by $p > 0.05$ and the null hypotheses apply, the mean of both variables has to be practically in this margin (figure 3.11) and thus the equivalence is proven.

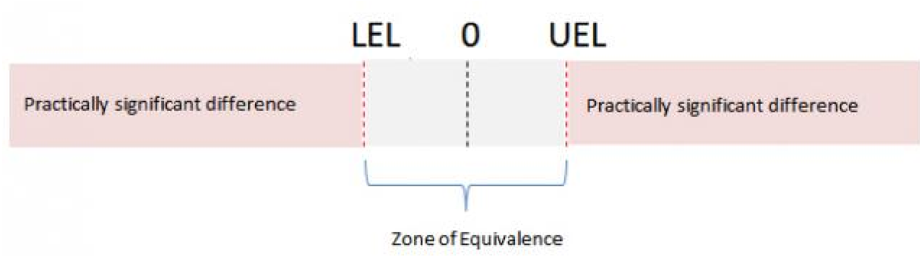

Figure 3.11: Zone of Equivalence[44]

The critical part of the equivalence test is the determination of the equivalence margin $\pm\delta$. Depending on the width of the margin an equivalence of two data rows is rejected or applied. Most of the literature [45][42][43] does not give a standard for the analysis, but it is rather up to everyone to determine the margin. In this work the $\pm\delta$ is based on the standard deviation, because it shows how the data behaves around its mean. Additionally the standard deviation is divided by two to obtain a more narrow range of equivalence.

To identify the data sets, which could be equivalent, a pre-selection is performed by checking the data for difference. The right way to do so is either with a paired t-test, when the data is normally distributed or the Wilcoxon signed-rank test [46][47], when the data is not. In both ways the data has to be at least ordinal scaled, which is the case. Thus the data is checked for normal distribution with the Shapiro-Wilk-Test.

In figure 3.12 the work flow for the statistical approach is presented.

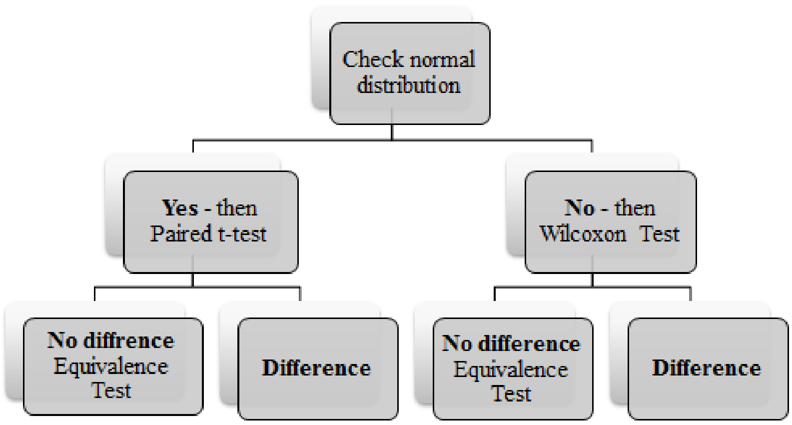

Figure 3.12: Work flow for the statistical analysis

For all tests besides the equivalence tests, the statistic software SPSS from $IBM^{®}$ (IBM Version 20.0.0 for Mac) is used. The equivalence test is performed with $Minitab^{®}$

(Minitab, Inc version 17.3.1)[2].

Besides the equivalence test for the angles, a second way of comparison is used to analyze the similarities within these measurement methods. An individual way of analyzing these items is performed by a percentage agreement. Onate et al.[8] already did the same by comparing the LESS scores with a 3D Vicon System. The 3D-Motion data and the Shape data are transformed by the categorization from tables 3.1 to 3.10. The data is now separated in scores of 0, 1 and 2. Out of this the number of equal scores between 3D-Motion data and rater and respectively 3D-Motion data and markerless data is expressed in percentage of all scores. Therefore, a definition of poor (less than 50% agreement), moderate (51-79% agreement) and excellent (80% and higher agreement) is used (see table 3.11). For example, if 70 out of 110 scores are equal, then a percentage agreement would be 63.6%, because 70 would be divided by 110.

Table 3.11: Categorization of the percentage agreement

Percentage	Interpretation
$\leq 50\%$	poor agreement
$51\% - 79\%$	moderate agreement
$\geq 80\%$	excellent agreement

[2] http://www.minitab.com/de-de/products/minitab/education/

4 Results

In the following chapter the results from all return to sport movements are presented. As this work is focused on the evaluation of markerless tracking as a favorable method for the return to sport question, this will be presented last. First of all the results of the 2-D rater-based inspection in comparison to the gold standard are shown. The interpretation will be more precise, if each criteria is analyzed solely and the reason for the results can be pointed out quicker.

As mentioned above, in figure 3.12, a test of normal distribution is performed to ensure that the right statistical method is applied. The markerless and the marker data are not normally distributed, if the Shapiro-Wilk-Test denies the alternative hypothesis with $p < 0.05$.

Table 4.1: Shapiro-Wilk-Test for normal distribution for marker-based vs. markerless, rater-based and hybrid motion tracking

Criteria	Markerless	Rater-based	Hybrid
All	$p = 0.46$	$p = 0.094$	$p = 0.85$
Hip Stability	$p = 0.46$	-	$p = 0.85$
Tibia/Knee	$p < 0.01$	-	$p < 0.01$
Pelvis Stability	$p = 0.86$	$p = 0.094$	$p = 0.05$
Shock Absorption	$p = 0.63$	$p = 0.061$	$p = 0.85$
Thigh Angle	$p = 0.9$	$p = 0.102$	$p = 0.44$
Trunk Stability	$p = 0.91$	$p = 0.008$	$p = 0.88$
Trunk Angle	$p = 0.26$	$p = 0.552$	$p = 0.22$

For the criteria Tibia/Knee of the marker-based vs. markerless comparison the Wilcoxon-signed-rank-test is used and for all others the paired t-test. All criteria of the marker-based vs. rater-based, despite Trunk Stability can be analyzed with the paired t-test. For the marker-based vs. Hybrid evaluation the Wilcoxon-signed-rank test is performed for Tibia/Knee and Pelvis Stability. The others are evaluated with the paired t-test.

The hypothesis for the Wilcoxon and paired t-test are phrased as followed:

- *Null-Hypothesis*: There is a no significant difference between the angles of markerless and marker-based tracking. ($p > \alpha$-significance)
- *Alternative-Hypothesis*: There is a significant difference between the angles of markerless and marker-based tracking. ($p < \alpha$-significance)

The α-level is set to 0.05 for the complete work. The same applies to the 2D-rating, the marker-based tracking and the Hybrid-tracking:

All criteria are analyzed together and additionally each criteria will be presented individually.

4.1 Total score

The total test score from the 2D-Rating is in mean higher than the marker-based and markerless tracked scoring with $2 \pm 2.74SD$. (See table 4.2)

Table 4.2: Total Score in Comparison

	Total Score				Differences to marker-based		
Subject	Marker	Markerless	2D Score	Hybrid	2D	Markerless	Hybrid
1	32	35	38	37	6	3	−5
2	28	32	31	30	3	4	−2
3	39	38	41	38	2	−1	1
4	27	27	32	30	5	−1	0
5	32	29	34	29	2	−3	3
6	37	37	34	39	−3	0	−2
7	34	37	39	35	5	3	−1
8	30	33	29	32	−1	3	−2
				Mean	2	1	−1
				SD	2.74	2.4	2.23

4.2 Rater-based evaluation

4.2.1 Inter-rater-reliability

The inter-rater-reliability to access the accuracy of the raters among each other is with ICC=0.99 for the angles and ICC=0.96 for the scores excellent. Furthermore the standard deviation of the means within all five raters is with a value of $\pm 1.97°$ good.

Table 4.4: Inter-rater-reliability for rater-based angles

Criteria	Mean $\pm$ SD angles	Inter-rater-reliability
All	20.58 ± 1.97	0.99
Pelvis stability	4.7 ± 1.24	0.95
Shock Absorption	28.31 ± 2.05	0.98
Thigh Angle (Hip)	32.48 ± 2.09	0.98
Trunk Angle (Hip)	26.7 ± 2.59	0.98
Trunk Stability	5.4 ± 1.62	0.92

4.2.2 Test for difference

The null hypothesis for the comparison of all marker-based criteria vs. 2D-rater-based criteria is rejected with $p = 0.001$, which means that the complete data set, gained with 2D visual inspection, differentiates significantly from the 3D-marker-based tracking. Split down to each criteria solely, the same applies to the Shock Absorption ($p = 0.001$), Thigh Angle ($p = 0.001$) and Trunk Stability ($p = 0.012$). Pelvis Stability and Trunk Angle (Hip Strategy) have both greater p-value than the alpha-level of $\alpha = 0.05$, which leads to the conclusion that these two are not different and can be considered nearly the same. (Table 4.5)

Table 4.5: Results of the paired t-test for rater-based vs. marker-based

Criteria	test statistic t-value	p-value
All	7.735	0.001
Pelvis stability	1.335	0.192
Shock Absorption	7.722	0.001
Thigh Angle (Hip)	5.903	0.001
Trunk Angle (Hip)	0.955	0.345
Trunk Stability	2.636	0.012

The Trunk Stability is calculated with the Wilcoxon-signed-rank-test and results in a rejection of the null hypothesis ($z = -2.742$, $p = 0.006$). Thus, the Trunk Stability is significantly different between 2D-rater-based and marker-based 3D-Motion tracking.

4.2.3 Equivalence test for rater-based tracking

The fact, that the Hip Stability and Tibia/Knee Position for 2D-scoring is not quantified disables the comparison based on angles. According to table 4.5 there is a significant difference for all, the Hip Stability, Thigh Angle, Shock Absorption and Trunk Stability.

In the following tables SD means standard deviation, SE means standard error, CI coincidence interval and DF is the abbreviation for degrees of freedom.

Pelvis Stability:

Table 4.6: Descriptive statistics for Pelvis Stability - rater-based vs. marker-based

Difference	SD	SE	95% CI	Margin
-1.0457	3.0412	0.53761	(-1.9573;0)	(-1.5;1.5)

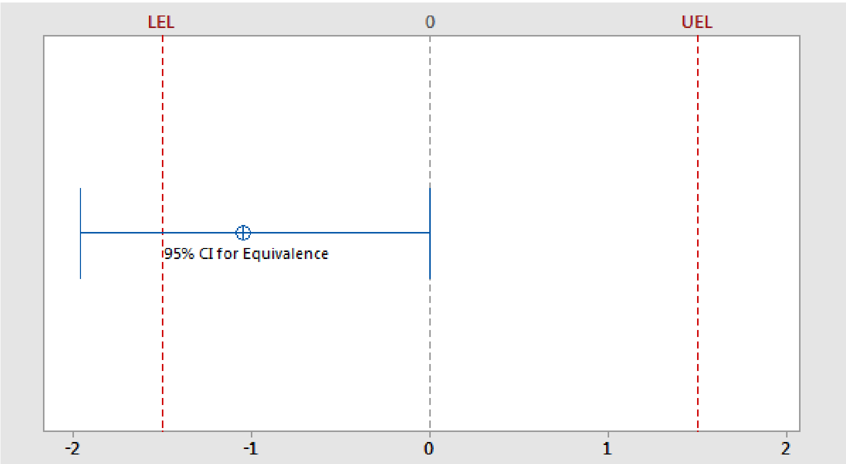

Figure 4.1: Equivalence Test: Pelvis Stability rater-based vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.7: Results of equivalence test for Pelvis Stability - rater-based vs. marker-based

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -1.5	31	0.84499	0.202
Difference $\geq$ 1.5	31	-4.7352	0.001

The greater of the two p-values is 0.202, thus equivalence cannot be claimed.

Trunk Angle:

Table 4.8: Descriptive statistics for Trunk Angle (Hip) - rater-based vs. marker-based

Difference	SD	SE	95% CI	Margin
-1.0107	4.3952	0.63439	(-2.0751;0.053794)	(-2.15;2.15)

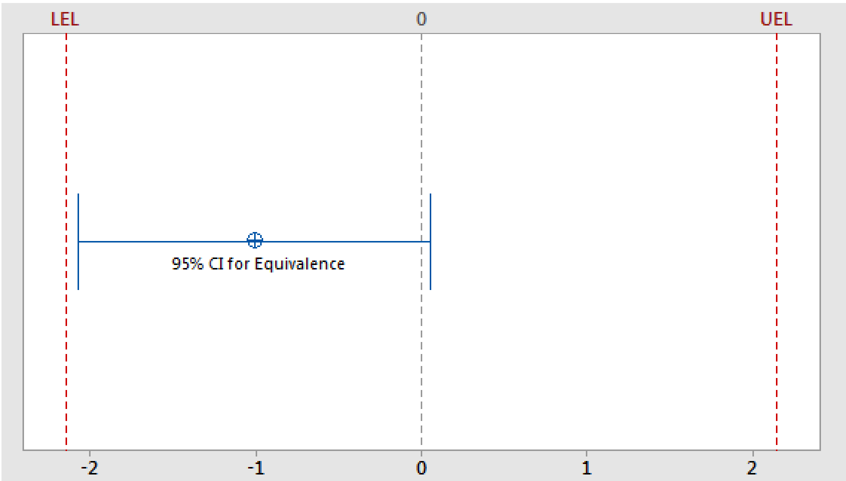

Figure 4.2: Equivalence test: Trunk Angle rater-based vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.9: Results of equivalence test for Trunk Angle (Hip) - rater-based vs. marker-based

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -2.15	47	1.7959	0.039
Difference $\geq$ 2.15	47	-4.9822	0.001

Both p-values are smaller than 0.05 and the equivalence can be claimed. Trunk Angle is the only criteria, which is equivalent for marker-based tracking and rater-based inspection. All other criteria, including the total data set, show a significant difference.

4.2.4 Percentage agreement for rater-based tracking

The percentage agreement for the marker-based and 2D-Rater Scoring is shown in table 4.10 for all criteria. There is an overall moderate agreement (78.3%). For the Trunk Angle and Knee Position an almost perfect agreement is achieved. Poor agreement is only achieved by the Shock Absorption with 59.4%. The Hip Stability comes to a value of (64.6%), which is still considered as moderate.

Table 4.10: Results of percentage agreement rater-based vs. marker-based

Criteria	amount of agreement	total	percentage
All	227	290	78.3%
Hip Stability	31	48	64.6%
Pelvis Stability	24	32	75%
Trunk Stability	30	40	75%
Thigh Angle (Hip)	41	48	85.4%
Trunk Angle (Hip)	45	48	93.7%
Shock Absorption	19	32	59.4%
Knee Position (Hip)	37	40	92.5%

4.3 Markerless 3D-Motion tracking

4.3.1 Test for difference

The null hypothesis, saying that the angles of markerless and marker-based tracking are not significantly different is rejected, by a p-value of $p = 0.001$.

With a p-value of 0.001 for the Trunk Angle (Hip Stability) and 0.029 for Trunk Stability, the null-hypothesis is rejected as well and there are significant differences between markerless and marker-based tracking for the Trunk Angle and Trunk Lean.

On the other side the null hypothesis applies for the Hip Stability, the Pelvis Stability and the Thigh Angle with p-values of 0.142, 0.463 and 0.168. The Shock Absorption criteria is close to the alpha-level with $p = 0.07$, but could be still considered as not significantly different. This indicates that those angles are pretty similar.

Table 4.11: Results of the paired t-test for markerless vs. marker-based

Criteria	test statistic t-value	p-value
All	3.796	0.001
Hip Stability	1.493	0.142
Pelvis stability	-0.743	0.463
Shock Absorption	1.870	0.07
Thigh Angle (Hip)	1.400	0.168
Trunk Angle (Hip)	3.786	0.001
Trunk Stability	2.262	0.029

The Tibia/Knee Position is calculated with Wilcoxon-signed-rank-test, because there is no normal distribution of the data. With $z = -0.977$ and $p = 0.329$ the Tibia/Knee Position has no difference between marker-based and markerless tracking and can be checked for equivalence, like the others.

4.3.2 Equivalence tests for markerless tracking

Hip Stability:

Table 4.12: Descriptive statistics for Hip Stability - markerless vs. marker-based

Difference	SD	SE	95% CI	Margin
-0.00416	0.0193	0.00279	(-0.00884;0.00052)	(-0.01;0.01)

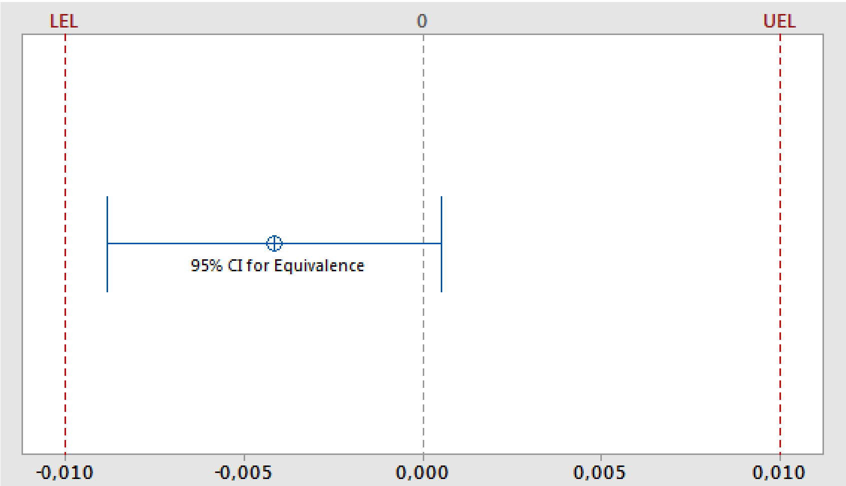

Figure 4.3: Equivalence test: Hip Stability markerless vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.13: Results of equivalence test for Hip Stability - markerless vs. marker-based

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -0.01	47	2.0908	0.021
Difference $\geq$ 0.01	47	-5.0777	0.001

The greater of the two p-values is 0.021, which is less than 0.05 proves equivalence of Hip Stability between marker-based and markerless tracking.

Pelvis Stability

Table 4.14: Descriptive statistics for Pelvis Stability - markerless vs. marker-based

Difference	SD	SE	95% CI	Margin
-0.5116	3.8945	0.6884	(-0.6556;1.6789)	(-1.9;1.9)

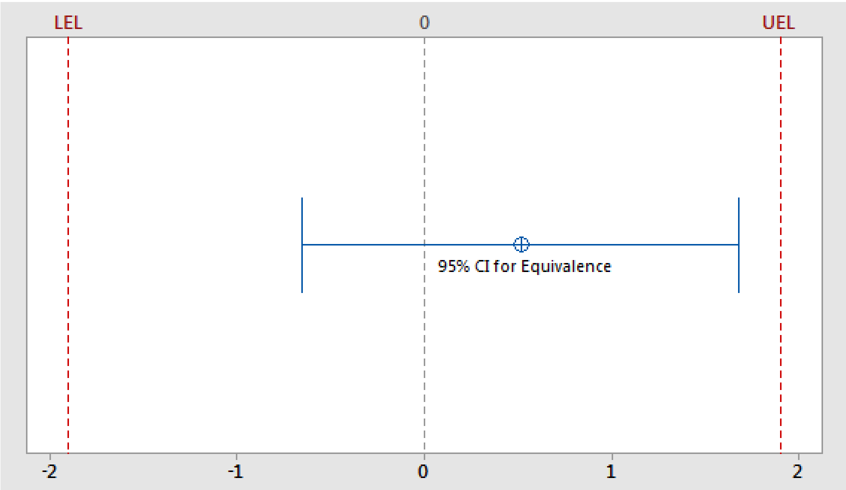

Figure 4.4: Equivalence test: Pelvis Stability markerless vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.15: Results of equivalence test for Pelvis Stability - markerless vs. marker-based

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -1.9	31	3.5031	0.001
Difference $\geq$ 1.9	31	-2.0167	0.026

None of the two p-values is greater than $\alpha = 0.05$ and leads to claim of equivalence for pelvis stability.

Thigh Angle

Table 4.16: Descriptive statistics for Thigh Angle - markerless vs. marker-based

Difference	SD	SE	95% CI	Margin
-0.892	4.41489	0.6372	(-1.9613;0.1771)	(-2.2;2.2)

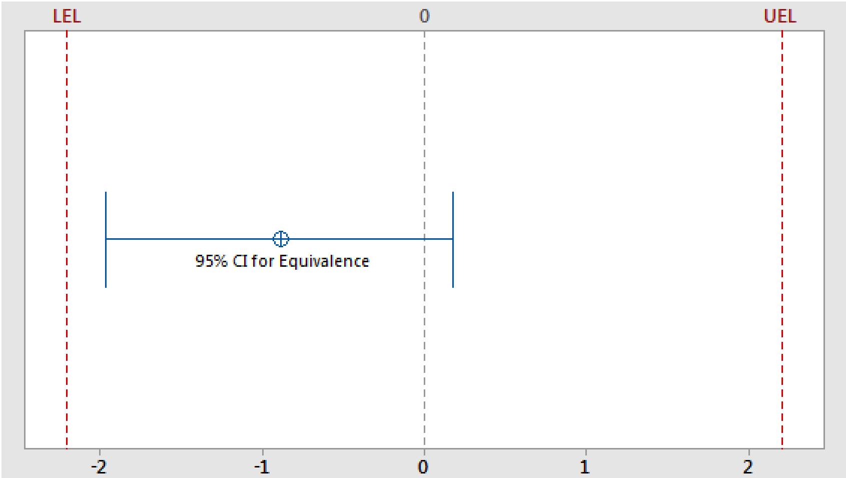

Figure 4.5: Equivalence test: Thigh Angle markerless vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.17: Results of equivalence test for Thigh Angle - markerless vs. marker-based

Null hypothesis	DF	t-Value	p-Value
Difference ≤ -2.2	47	2.0525	0.023
Difference ≥ 2.2	47	-4.8524	0.001

Equivalence can be claimed, because both p-values are smaller than 0.05.

Shock Absorption

Table 4.18: Descriptive statistics for Shock Absorption - markerless vs. marker-based

Difference	SD	SE	95% CI	Margin
-1.3646	4.1271	0.7296	(-2.6016;0)	(-2;2)

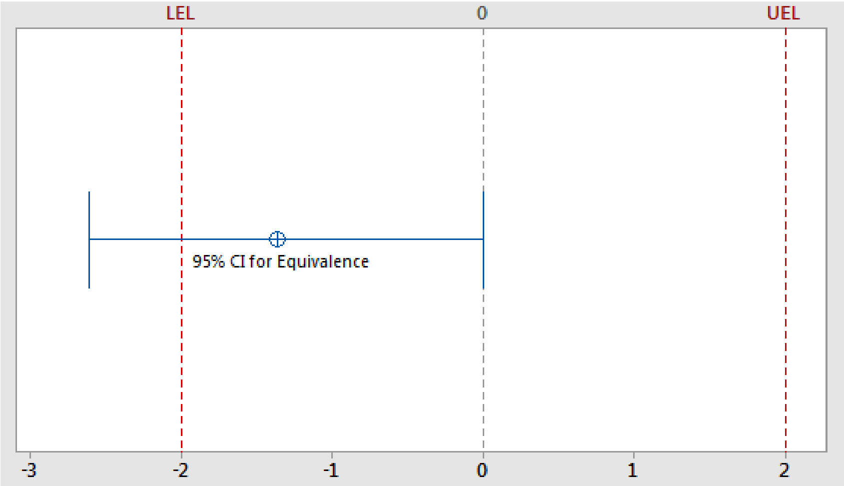

Figure 4.6: Equivalence test: Shock Absorption markerless vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.19: Results of equivalence test for Shock Absorption - markerless vs. marker-based

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -2	31	2.8709	0.195
Difference $\geq$ 2	31	-4.6117	0.001

The greater of the two p-values is 0.195. An equivalence of both methods cannot be claimed.

4.3.3 Percentage agreement for markerless tracking

The percentage agreement for the marker-based and marker-less tracking is shown in table 4.20 for all criteria. There is an overall excellent agreement, although it is at the lower level of the categorization (85.86%). For the Thigh Angle, Trunk Angle and Knee Position an almost perfect agreement is achieved. The lowest agreement is achieved for the Pelvis Stability (59%) which can still be considered as moderate.

Table 4.20: Results of percentage agreement markerless vs. Marker-based

Criteria	amount of agreement	total	percentage
All	249	290	85.86%
Hip Stability	41	48	85.42%
Pelvis Stability	19	32	59.4 %
Trunk Stability	32	40	80 %
Thigh Angle (Hip)	45	48	93.75%
Trunk Angle (Hip)	46	48	95.8 %
Shock Absorption	26	32	81.25%
Knee Position (Hip)	40	40	100 %

4.4 Hybrid 3D-Motion tracking

4.4.1 Test for difference

The null hypothesis, saying that the angles of marker-based tracking and Hybrid motion tracking are not significantly different applies, by a p-value of $p = 0.16$. This means that both methods are not different from each other. All other criteria, which are tested with the paired t-test, reject the alternative hypothesis with p-values greater than 0.05.

Table 4.21: Results of the paired t-test for marker-based vs. hybrid

Criteria	test statistic t-value	p-value
All	1.408	0.16
Hip Stability	0.248	0.805
Shock Absorption	1.05	0.302
Thigh Angle (Hip)	0.412	0.682
Trunk Angle (Hip)	0.606	0.548
Trunk Stability	1.383	0.173

The results of the Wilcoxon-signed-rank-test for Tibia/Knee and Pelvis Stability are $z = -0.558$, $p = 0.577$ and $z = -1.646$, $p = 0.1$ leading to a rejection of the alternative hypothesis and the claim that both criteria do not differentiate.

This leads to the next step, where the six criteria are tested for equivalence to ensure a real valid similarity.

4.4.2 Equivalence test for hybrid tracking

All criteria

Table 4.22: Descriptive statistics for all criteria - marker-based vs. hybrid

Difference	SD	SE	95% CI	Margin
-0.2573	3.101	0.1827	(-0.5589;0.0442)	(-1.5;1.5)

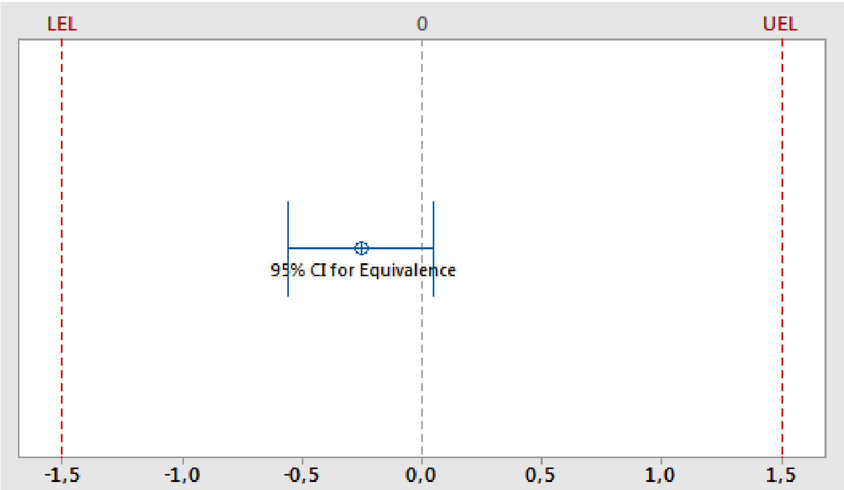

Figure 4.7: Equivalence Test: All criteria hybrid vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.23: Results of equivalence test for All criteria - marker-based vs. hybrid

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -1.5	287	6.798	0.001
Difference $\geq$ 1.5	287	-9.6152	0.001

Both p-values are smaller than 0.001. An equivalence of both methods can be claimed.

Hip Stability

Table 4.24: Descriptive statistics for Hip Stability - marker-based vs. hybrid

Difference	SD	SE	95% CI	Margin
-0.007	0.002	0.0029	(-0.0056;0.0042)	(-0.01;0.01)

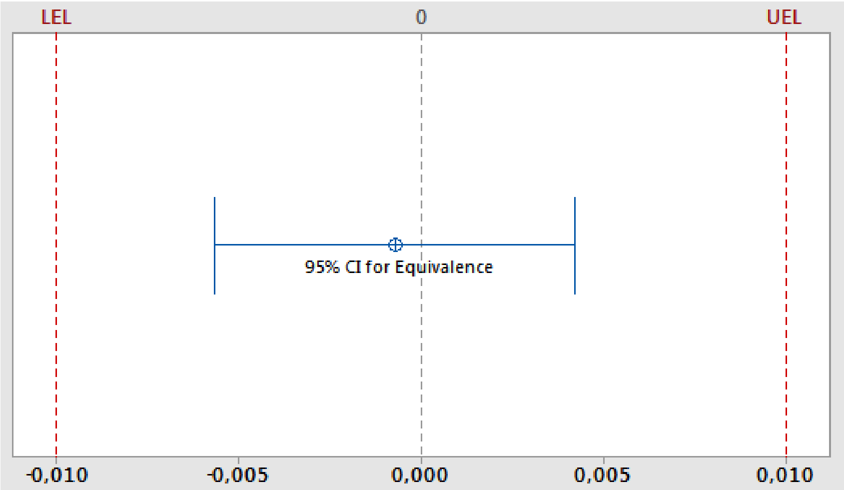

Figure 4.8: Equivalence Test: Hip stability hybrid vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.25: Results of equivalence test for Hip Stability - marker-based vs. hybrid

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -0.01	47	3.1514	0.001
Difference $\geq$ 0.01	47	-3.6472	0.001

The p-values for the upper level of equivalence and the lower level are both smaller than 0.001. So the equivalence of both methods can be claimed.

Tibia/Knee Position (Hip)

Table 4.26: Descriptive statistics for Tibia/Knee Position - marker-based vs. hybrid

Difference	SD	SE	95% CI	Margin
-0.02	0.117	0.018	(-0.0112;0.0515)	(-0.06;0.06)

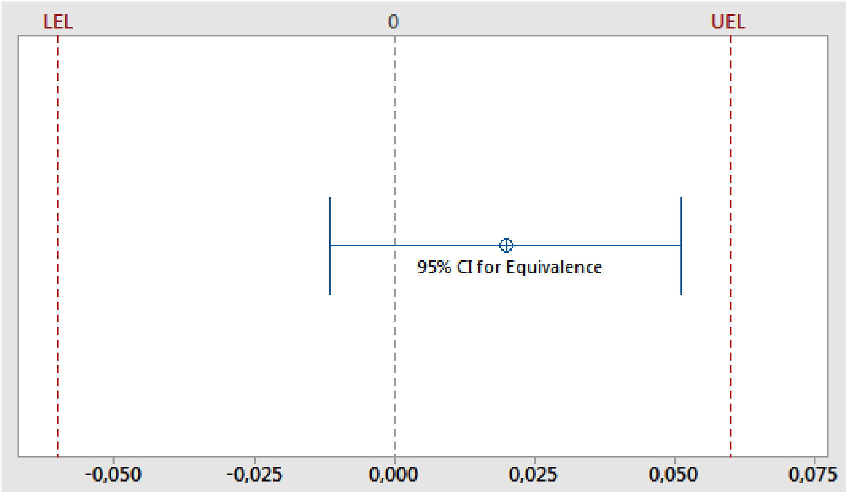

Figure 4.9: Equivalence test: Tibia/Knee Position hybrid vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.27: Results of equivalence test for Tibia/Knee Position - marker-based vs. hybrid

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -0.06	39	4.301	0.001
Difference $\geq$ 0.06	39	-2.146	0.019

The greater of the two p-values is 0.019, which is still less than $\alpha = 0.05$. Therefore, equivalence can be claimed for Tibia/Knee position.

Pelvis Stability

Table 4.28: Descriptive statistics for Pelvis Stability - marker-based vs. hybrid

Difference	SD	SE	95% CI	Margin
0.387	2.75	0.487	(-0.439;1,214)	(-1.45;1.45)

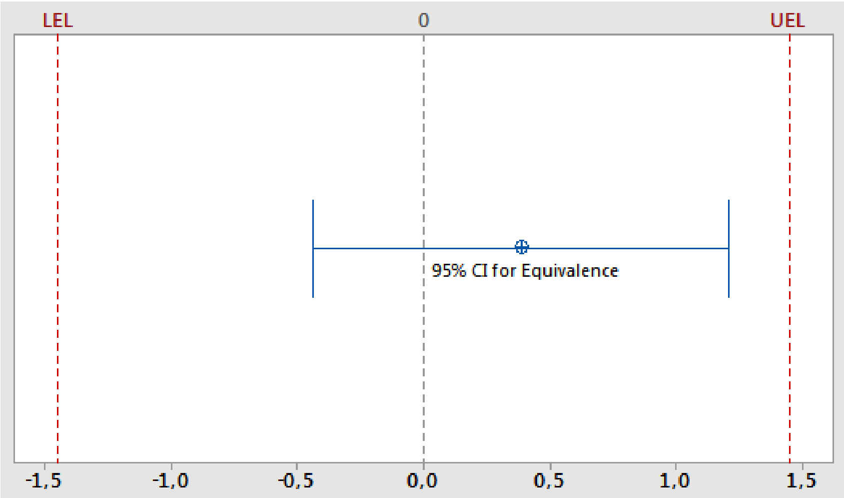

Figure 4.10: Equivalence test: Pelvis Stability hybrid vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.29: Results of equivalence test for Pelvis Stability - marker-based vs. hybrid

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -1.45	31	3.77	0.001
Difference $\geq$ 1.45	31	-2.179	0.019

The greater of the two p-values is 0.019, which is still less than $\alpha = 0.05$. Therefore, equivalence can be claimed for Pelvis Stability.

Shock Absorption

Table 4.30: Descriptive statistics for Shock Absorption - marker-based vs. hybrid

Difference	SD	SE	95% CI	Margin
0.737	3.97	0.702	(-1.928;0.453)	(-2;2)

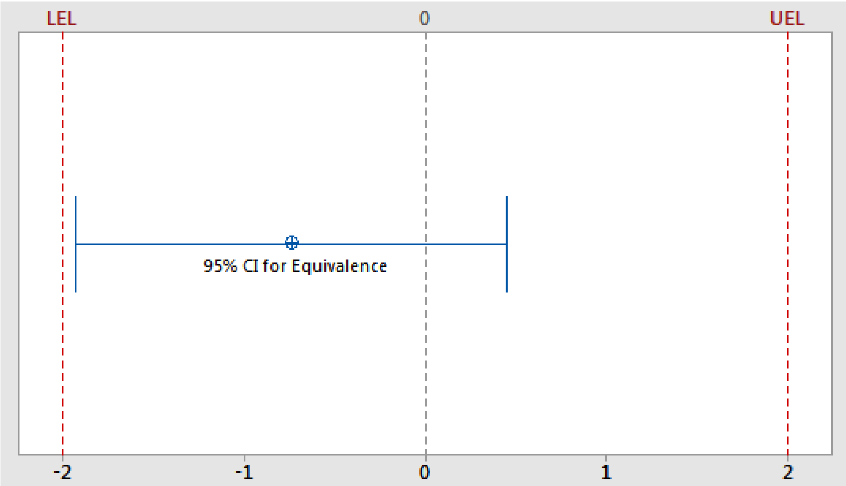

Figure 4.11: Equivalence test: Shock Absorption hybrid vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.31: Results of equivalence test for Shock Absorption - marker-based vs. hybrid

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -2	31	1.798	0.041
Difference $\geq$ 2	31	-3.749	0.001

The greater of the two p-values is close to $\alpha = 0.05$ but still smaller with 0.041, which leads to the claim of equivalence for Shock Absorption.

Thigh Angle (Hip)

Table 4.32: Descriptive statistics for Thigh Angle - marker-based vs. hybrid

Difference	SD	SE	95% CI	Margin
0.247	4.15	0.599	(-1.252;0.758)	(-2;2)

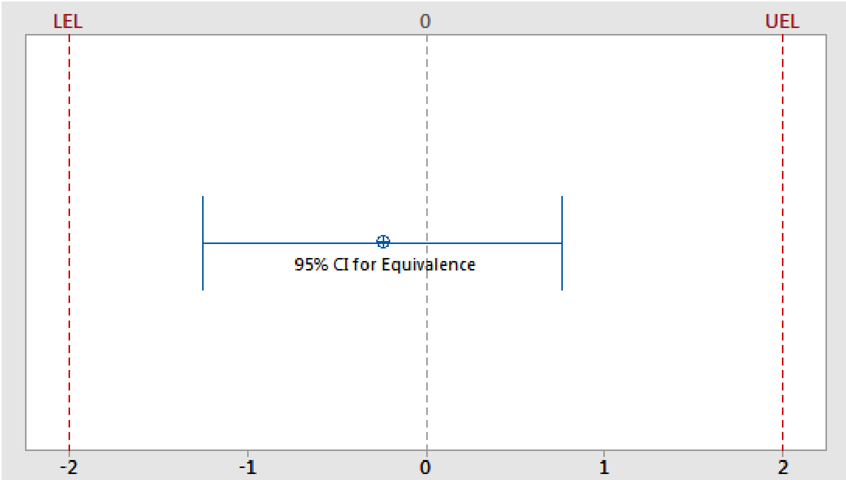

Figure 4.12: Equivalence test: Thigh Angle Hybrid vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.33: Results of equivalence test for Thigh Angle - marker-based vs. hybrid

Null hypothesis	DF	t-Value	p-Value
Difference ≤ -2	47	2.926	0.003
Difference ≥ 2	47	-3.749	0.001

The greater of the two p-values is 0.003. Therefore, equivalence can be claimed for Thigh Angle.

Trunk Angle (Hip)

Table 4.34: Descriptive Statistics for Trunk Angle - marker-based vs. hybrid

Difference	SD	SE	95% CI	Margin
-0.958	4.8	0.693	(-2.121;0.205)	(-2.35;2.35)

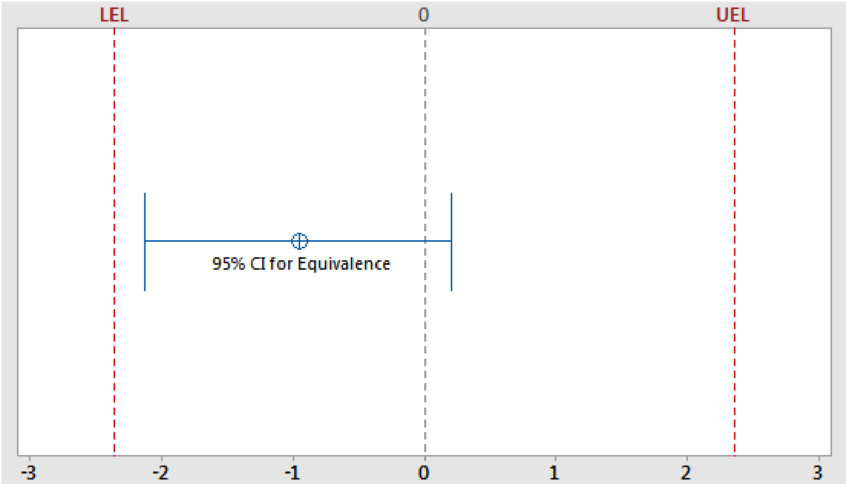

Figure 4.13: Equivalence test: Trunk Angle hybrid vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.35: Results of equivalence test for Trunk Angle - marker-based vs. hybrid

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -2.35	47	2.008	0.025
Difference $\geq$ 2.35	47	-4.773	0.001

The greater of the two p-values is 0.025, which is still less than $\alpha = 0.05$. Therefore, equivalence can be claimed for Trunk Angle.

Trunk Stability

Table 4.36: Descriptive statistics for Trunk Stability - marker-based vs. hybrid

Difference	SD	SE	95% CI	Margin
-0.146	1.53	0.242	(-0.554;0.261)	(-0.75;0.75)

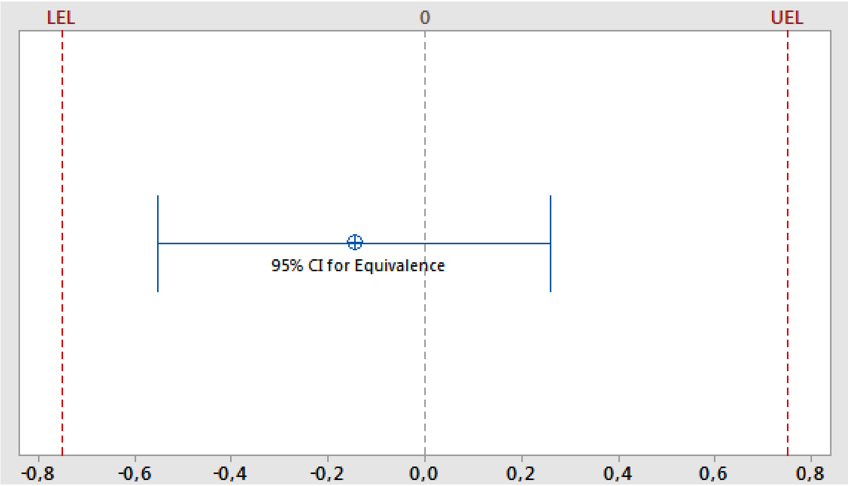

Figure 4.14: Equivalence test: Trunk Stability hybrid vs. marker-based with mean 95% Confidence Interval, as well as the LEL and UEL

Table 4.37: Results of equivalence test for Trunk Stability - marker-based vs. hybrid

Null hypothesis	DF	t-Value	p-Value
Difference $\leq$ -0.75	39	2.496	0.008
Difference $\geq$ 0.75	39	-3.708	0.001

The greater of the two p-values is 0.008. The equivalence of the Trunk Stability criteria for marker-based tracking and hybrid tracking can be claimed.

4.4.3 Percentage agreement for hybrid tracking

An overall almost excellent agreement of Hybrid and marker-based motion tracking is achieved with 86.56%. Pelvis Stability is with a value of 65.63% the weakest of all, but it is still in the moderate margin.

Table 4.38: Results of percentage agreement for marker-based motion tracking vs. hybrid Motion tracking

Criteria	amount of agreement	total	percentage
All	251	290	86.56%
Hip Stability	39	48	81.26%
Pelvis Stability	21	32	65.63%
Trunk Stability	36	40	90 %
Thigh Angle (Hip)	46	48	95.83%
Trunk Angle (Hip)	42	48	87.5 %
Shock Absorption	27	32	84.38%
Knee Position (Hip)	40	40	100 %

In comparison to markerless motion tracking table 4.20 the hybrid tracking method delivers no real improvement of the percentage agreement. The Pelvis Stability is improved by two (6.23%), the Shock Absorption and thigh angle by one. Trunk Stability achieves an improvement of four, which is an improvement of 10%. Hip Stability impaired by two (4.16%) and Trunk Angle by a value of four(8.3%). The other criteria remain unchanged.

5 Discussion

In the first part of this work rater-based screening and markerless tracking are compared to the gold standard 3D-marker-based tracking. The basis for this investigation is the MPI Return to sport screening. The results from Chapter 4 are discussed in the following.

Inter-rater-reliability

First, the ICC for rater-based scoring is perfect. The value of 0.99 and the standard deviation of ±1.97° show how good the raters agree with each other for the angle measurement. As a consequence hypothesis 1 has to be rejected. According to the educational background of the rater, these results are not surprising. Four out of five raters work in the same institution and perform this return to sport screening frequently. This ensures a good inter-rater-reliability. But this might only be consistent in case clinicians work with the same standard and same education over a long period of time. The point of time where the scoring is performed was fixed in this case. Usually the raters have the possibility to chose the scoring moment their selves. This could definitely lead to deviations in the inter-rater-reliability. Additionaly only five raters where observed. The probability that the reliability decreases, if more raters are included, is high. Publications like Shultz et. al[48] and Maclachlan et. al.[13] show weaker inter-rater-reliability for return to sport screenings. This leaves the question about inter-rater-reliability still unanswered. For the further investigation in this work these results are a favorable basis. The mean value of the five raters is a solid value to compare with.

Rater-based vs. marker-based

The rater-based total score is in average 2 (SD ±2.74) points higher than the 3D-marker-based tracking. The equivalence testing proves that rater-based tracking is measured higher than marker-based too. The mean differences and even the 95% coincidence intervall (CI) are always negative.(Figure 4.1) This is also emphazised by McLean et. al. [49], but controversial to the findings of Maclachlan et al. [13], who found out that observer-ratings underestimate faster sport movements.

As expected, the rater-based inspection delivers significantly different results than the marker-based tracking. Only for Pelvis Stability and Trunk Angle (Hip) a difference is proven wrong, but in a more precise analysis the Trunk Angle (Hip) criteria is the only one proven to be equivalent, even though it was barley in the 95%-CI (Fig.4.2). So the second hypothesis (H2) is proven to be right.

A reason for these results could be out of plane movement by the leg or even the whole body, which falsifies the 2D-measuring with a goniometer. Marker-based 3D-Motion tracking is due to the multiple camera setup not affected. A more precise observer-rating might be achieved, if the video resolutions are very high (e.g. 1 Megapixel and more). The rater could identify the anatomical landmarks easier, when performing the measurements on the desktop screen. It would allow a larger zoom and preciser usage of the gonimeter.

On the other hand the scoring system reveals an actually good agreement of marker-based tracking and rater-based inspection. It ranges from 64.6% to 93.7% and reaches an overall agreement of 78.3%.(Fig.5.1)
One problem for the average matching of Hip Stability is the fact that in rater-based evaluation the Hip Stability is only evaluated qualitative. That means it is a more subjective decision when it comes to a smaller range of motion. This is also proven by Maclachlan et al.[13]. Even though Knee Position is a qualitative analysis in rater-based screening, it matches the marker-based scoring perfectly. This is referable to the dichotomous scoring which eases the matching.
The difference between those two analysis methods (percentage agreement and statistical equivalence) is explained by the different scaling levels. The scoring categorization includes a bigger range of angles (e.g. 5° to 15°), that allows a substantial bigger correlation. Even if the angles differ with 14° they can still achieve the same score.(e.g. Shock Absorption: 31 and 45 degrees are scored alike as 1) In contrast the angle measurement has a very narrow window to claim equivalence and does not allow a big variance in the differences.

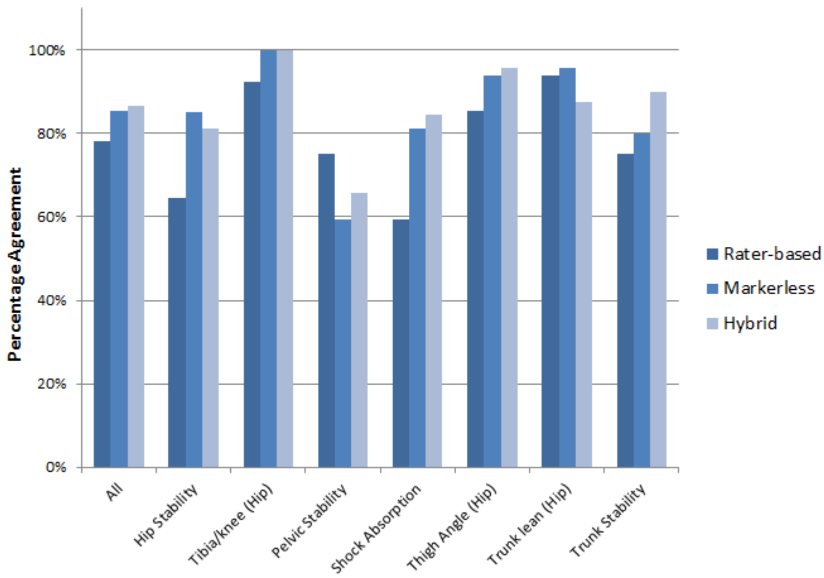

Figure 5.1: Overview of the percentage agreement for rater-based, markerless and hybrid tracking

Markerless vs. marker-based

Markerless and marker-based tracking deliver different values as well. As long as one compares exact angles and point of time there is no equivalence. Only for Hip Stability, Pelvis and Thigh Angle equivalence is claimable. All other criteria are significantly different. This is still a better result than for rater-based inspection.

When referring to the scores marker-based and markerless tracking achieve a good, almost perfect consistency (correlation).(Fig.5.1) The very good values for Thigh Angle (hip), Trunk Angle (hip) and Knee Position (hip) are achieved because of the dichotomous scoring. The probability that the angles are below or over a specific value are 50%. The other criteria are all separated in three categories and therefore change the probability of agreement to a third. The range for a score change (eg. from 2 to 1) in Pelvis and Trunk Stability is only 5 degrees, which makes it hard to achieve good correlations, according to this work [18]. This inaccuracy could be a reason why Pelvis Stability and Trunk Stability do not match. Furthermore, the problem of the silhouette tracking of the pelvis with Simi Shape emphasizes the difficulty to achieve a good result for Pelvis Stability.

It is very interesting that the percentage agreement of the Pelvis Stability is in an almost poor condition with 59%, but the equivalence test of this criteria claims an equivalence. The mean difference is around 0.9 deg, which is not bad but the standard deviation with ± 4.4 is very high. This huge variation may be referable to the difficulties in the hip tracking for markerless tracking and should be erasable with the hybrid method.

Table 5.1: Overview of the proven equivalence with marker-based 3D tracking for all evaluation systems

Criteria	rater-based	markerless	hybrid
All	x	x	✓
Hip Stability	x	✓	✓
Pelvis Stability	x	✓	✓
Trunk Stability	x	x	✓
Thigh Angle (Hip)	x	✓	✓
Trunk Angle (Hip)	✓	x	✓
Shock Absorption	x	x	✓
Knee Position (Hip)	x	x	✓

Hybrid vs. marker-based
The hybrid tracking delivers as expected better consistency with marker-based tracking. The markers which define the hip, allow a more steady position of the hip and therefore improve the results for Thigh Angle and Shock Absorption, as well as the Trunk Stability.

It is easier for Simi Shape to fit the model into the silhouette, because the pelvis is positioned by markers. The problem which comes along with the silhouette tracking of the pelvis are the iterations in which Shape tries to adjust the model perfectly. The pelvis is the crucial element/joint, which links the upper body to the lower body. Once the pelvis is in a fixed position and does not perform slight movements within the silhouette, all other body parts are more precise in the alignment between segment and silhouette. This is also confirmed by the equivalence test of the Pelvis Stability. The mean difference is only $0.38°$ (SD ± 2.75) compared to markerless with $-0.5°$ (SD ± 3.9).

Regarding each single angle hybrid tracking is claimed equivalent to the gold standard marker-based tracking. Whereas markerless tracking only proves equivalence for three criteria, Hybrid tracking is equivalent with marker-based tracking in all six criteria. Furthermore, the percentage agreement for Hybrid tracking is better than for markerless tracking. Due to the improvement of the hip tracking the agreement improved for Pelvis Stability, Shock Absorption and Thigh Angle. Even Trunk Stability improves the agreement by 10%.

While comparing methods at one point of time, it is difficult to achieve a complete consistency. There are always smaller issues, like marker-displacement by skin tissue-movement. Also, the marker were not attached by a schooled professional in this case, which could lead to deviation in the markers positions through all subjects. Some markers fell off during fast changes of direction or jumping tasks and had to be re-attached, leading to new positions of the lost markers. These problems are well known and would also occur in a clinical setting. Therefore, they are not a problem of this work, but a general issue of marker based systems. This is why all results should be treated with caution.

6 Conclusion and outlook to further possibilities of investigation

Rater-based inspection is not as accurate as the marker-based gold standard. Even though the percentage agreement delivers a good result, the actual angles measured with both methods are significantly different. The same applies to markerless tracking. This method is closer to the marker-based standard, but does not obtain the anticipated results. Hybrid tracking seems to be the perfect alternative to marker-based tracking. The equivalence of Hybrid and marker-based tracking is emphasized in this work. It improves the accuracy of tracking for difficult parts, such as the pelvis.

In contrast, the rater-based score has a good agreement with the gold standard when it comes to scoring. Well known that some agreements of the scores only happened by chance, these results are not really proven to provide the right statement. The ranges within the scores are still to large and therefore include a big range of motion. A correlation of different tracking methods needs to be treated with caution, due to the big ranges of agreement. But the same applies to markerless tracking as well. It delivers even better results.

Marker-based tracking is not practicable for screenings in the clinical daily routine. It is normally used in research projects, where time and money are not that essential. Every physical therapist has to screen a huge number of patients every day and is not able to attach markers for each patient solely. This is why markerless tracking is more worthwhile than any 3D-marker-based tracking system. Additionally markerless tracking is accompanied by the fact that it is more efficient for institutions to invest in. Human resources and education to gain a solid and reliable return to sport screening result out of rater-based inspection are less efficient than a one-time installed motion capture system. As mentioned earlier markerless tracking does not need education, besides a short instruction into the software. Once the markerless settings are set up for the screening, the tracking process is automatic and allows to screen and score patients more frequently and with less effort. Furthermore, a project to upload the captured motion data into a cloud is on its way. The idea behind this, would simplify and decrease the costs for institutions to track sport movements. They do not have to hire specialists for screenings anymore or invest in educational schoolings. Another factor to emphasize the usage of markerless tracking, is the ability to determine the perfect point of time for the evaluation, the lowest point of the center of mass, for example. This ensures a consistent point of time and minimizes the margin of error throughout all raters.

At the end the hybrid tracking should be the first choice for return to sports screenings.

It is reliable and valid and delivers accurate results on one hand and on the other it is not as time consuming and expensive as the marker-based tracking. Even for the few markers, which are used in the hybrid method, no education is needed. The marker position can be edited in Shape and therefore, optimize the implementation of hybrid tracking. But Hybrid is still more costly than markerless tracking, due to the fact that even the few markers have to be tracked separately, before they are implemented in the silhouette-based tracking. The implementation of IMUs (inertial measurement units) is another way to track hybrid.[50] Furthermore, hybrid tracking is not the only add-on option to improve the tracking process. Shape offers also a huge variety of settings, which can be individually customized. The amount of different data sets, e.g. joint centers, angles, etc. is high and could be helpful for further investigations in the return to sport question. Even dynamic data can be provided, which will be shown in part II.

All in all these facts emphasize again the favorable applicability of markerless tracking in the clinical field.

Part II
Evaluation of Joint Moment

7 Extended introduction

The idea behind the return to sport screenings, in general, is to draw a conclusion on the moments and forces in the knee, by identifing movement patterns that may predispose an individual to ACL injury. Those internal and external moments may cause a risk for the re-injury.[32][51][52][53] The problem is, as mentioned in part I of this work, that it is impossible to obtain force and moment data by simple visual inspection. Even if a force plate is included in a 2D-visual inspection, there is no inverse dynamics calculation without 3D-motion data. A lot of authors and scientists tried to get an idea of the coherence between movement patterns (e.g. pathological knee angles) and the forces caused by them.[33][54][30][31] But at the end there is no valid coherence. In this part of the work a new approach to the return to sport scoring is investigated. The idea and the data is still based on the work of part I.

The scores are an alternative to quantify the moments without any 3D-Motion equipment. According to [55][53][52][56][2][57] the sagittal plane movements and moments do not contribute to the change of ACL strain. The actual effect on the ACL strain is multiplanar, but more in the transverse and frontal plane. The combination of tibial rotation and valgus moment, which is called pivot shifting, increases the strain of the ACL. Shin et al. [58] found out that a valgus moment of 51 Nm combined with tibial internal rotation moment of 25.9 Nm increases the strain to a value of 0.105, which lies within the reported range of ACL rupture of 0.09-0.15. [56] Based on this fact only the valgus moment (frontal plane) and the internal rotation (transverse plane) are considered in the following approach. Due to the fact that all scores are added up to a single value, which decides over the athletes capability of returning safely to sport, the same should be done with the joint moments too. The idea behind this thought is to examine the connection between a movement score and the measured moment in the frontal and the transverse plane of the knee. Therefore, knee abduction moment and knee internal rotation moment are noted and compared to the single score of each movement to identify a coherence. This is only to evaluate a simple approach to the return to sport question. We are not trying to settle a specific value for categorization.

Due to the fact that marker-based 3D-Motion tracking is time consuming, especially the marker attachment, Shape could lead the way to a more time saving alternative. Right now there is no possibility to generate kinetic data out of usual markerless tracking, but with the features from Simi Shape there is an indirect way. Accuracy of kinematic markerless tracking is already evaluated and proven as reliable.[18][38] Therefore, this is a good situation for a first look on the kinetic data, in this case the moments for three joints. The high dynamic movements are a good test to analyze, whether markerless tracking via Shape can deliver accurate moments as well.

8 Extended methods

8.1 Hypotheses for moment evaluation

In this part of the work the moments, which seem to be crucial for the ACL injury mechanism, are compared to the scoring of the return to sport screening.

Hypothesis 5 (H5): Knee abduction moment and internal rotation moment correlate with the return to sport scoring.

Furthermore, Shape could simplify clinical investigations, if it was possible to obtain kinetic data. At the moment marker-based tracking is the only option to generate force and moment data, but Shape offers the possibility to track virtual marker and therefore, ease the process of data acquisition.

Hypothesis 6 (H6): Moments generated with the markerless tracking Software Shape correlate with the gold standard 3D-marker-based Motion tracking.

8.2 Correlation analysis of moments and return to sport scoring

The knee abduction moment and the internal rotation moment are picked from the same point of time as the return to sport scoring earlier on. The values of both moments are added up to a single value and are compared to the scoring. Additionally, the knee abduction moment and the internal rotation moment are checked for correlation with the score solely.

8.3 Calculation of joint moments in Simi Shape

The inverse dynamics of Motion offers the possibility to calculate moments and forces. For this option a force plate has to be included. Out of the ground reaction force (GRF) Motion determines the moments from distal to proximal. Shape transfers the motion data to Motion and the inverse dynamics is calculated automatically. By doing so there is no possibility to include force plate data. But Shape offers the option to track marker by itself. These markers are virtual markers (figure 8.1). The software projects markers, according the marker set from Simi Motion, on to the Shape model and provides the 3D-coordinate data from these markers.

The amount of markers that are used can be changed in the settings. If there is no 3D-marker data from real marker, the virtual markers do not need to be assigned with the marker on the subject and create their own position data, based on the Shape model.

After the tracking process the 3D marker data from Shape has to be exported to Simi Motion and is then available for further usage.

To complete the data sets for the inverse dynamics calculation the static trial needs to be reproduced. Therefore, the model in *Shape* is set up in the initial position, which is the same as for marker-based tracking (figure 8.1). The tracking for the static trial is only performed for approximately one second and is cut further on into a small data row. The produced 3D-data set can now be used for each movement of this subject. With all the single data sets as static trial, dynamic trial and the force plate data the final inverse dynamics known from the marker-based tracking can be calculated. Additionally the generated markerless data, as well as the 3D-marker-based data are filtered by a second order lowpass filter with 6 Hz. [18]

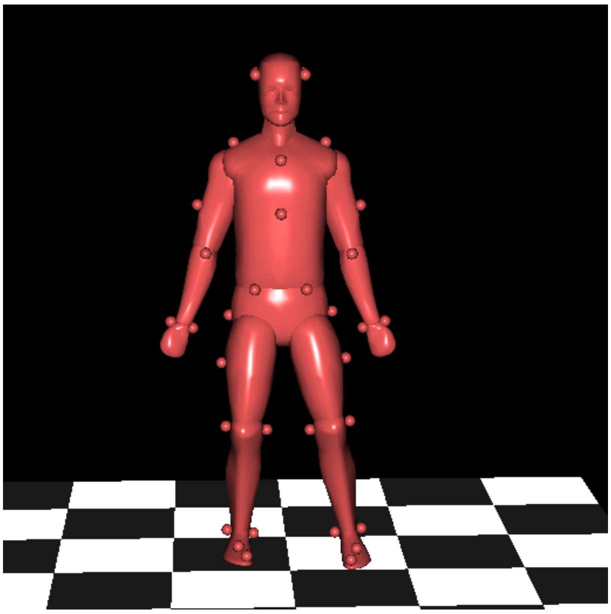

Figure 8.1: Shape Model with the corresponding virtual marker and the pose for the static trial

The approach to the data remains the same as above in part I. The muscle torques are taken from the same point of time as the scores earlier (Appendix B.1). Additionally, all data rows are time normalized and the moments are normalized to a average person with a weight of 75 kg and a height of 1.75m.

8.4 Statistics

The Spearman-rho correlation coefficient is used for both, the moment analysis with the scores and the torque comparison of markerless and marker-based tracking in this part. As well as the Wilcoxon-signed-rank-test the Spearman-rho correlation coefficient is a non

parametric measure for correlations and builds ranks for each value pair.
The data is time normalized in Simi Motion, to ensure the synchronization of the data points from Simi Motion and Shape. Afterwards, the data rows are exported into text-files and the correlation is calculated with Minitab[3] again.

As for this comparison the correlation is supposed to be very high, the following classification is applied:

Table 8.1: Classification of the Spearman's correlation coefficient

r_s	Interpretation
≤ 0.5	weak correlation
$0.5 - 0.8$	good correlation
≥ 0.8	perfect correlation

[3]See Chapter 3.5 Statistics for more information

9 Extended results

Only for six of the eight subjects valid force plate data could be generated, which results in a reduction of the amount of usable data sets. For the remaining six, the Step down does not include the force plate for the movement and is therefore eliminated for the further analysis.

9.1 Moment analysis

Table 9.1 shows the correlation for the single knee abduction moment (KAM) and internal rotation moment (IRM) with the score from the return to sport screening. "Total" means the addition of KAM and IRM to a total value. Afterwards, each movement is analyzed according to its score and moments. The total correlation is $r_s = 0.42$, which is a poor correlation. In contrast to that, Deceleration ($r_s = -0.81$) has a very good negative correlation. Lateral Shuffle is the only movements achieving a perfect correlation with $r_s = 0.9$. Side Step and Triple Jump are close to the poor categorization and therefore a solid but weak correlation. Drop Jump does not have any correlation between the moments and the return to sport screening.

Table 9.1: Spearman's correlation coefficient for KAM and IRM with scores from the return to sports screening

	KAM	IRM	Total	Deceleration	Drop Jump	Lateral Shuffle	Side Step	Triple Jump
r_s	0.23	0.49**	0.42*	-0.81*	0.19	0.95**	0.55	0.54

**The correlation is with 0.01-niveau significantly

*The correlation is with 0.05-niveau significantly

9.2 Accuracy of torques - markerless vs. marker-based

Only one very good example will be presented for the following joints. All other remaining are summed up in the mean correlation over all values obtain from the data sets.

9.2.1 Ankle torques

When comparing the correlation for the ankle supination, weak results can be achieved with a mean correlation of 0.362 over all ankle supination/pronation torques. There are some correlations, which are very low like 0.066, but also excellent results like 0.879 (figure 9.1).

Table 9.2: Descriptive Analysis for each movement of the ankle in in all planes normalized to average person(Nm/BW*BH)

	X-Plane		Y-Plane		Z-Plane	
	Mean	SD	Mean	SD	Mean	SD
All	-0.32	9.73	-11.63	11.22	-2.96	3.16
Decleration	8.06	12.42	-15.34	9.49	-3.17	3.49
Drop Jump	-4.66	9.77	-11.04	20.27	-5.81	3.92
Lateral Shuffle	-7.86	12.02	-13.40	12.53	-1.85	3.36
Side Step	1.35	9.87	-10.79	9.16	-2.60	3.04
Triple Jump	-7.29	10.27	-13.99	20.26	-4.49	3.93

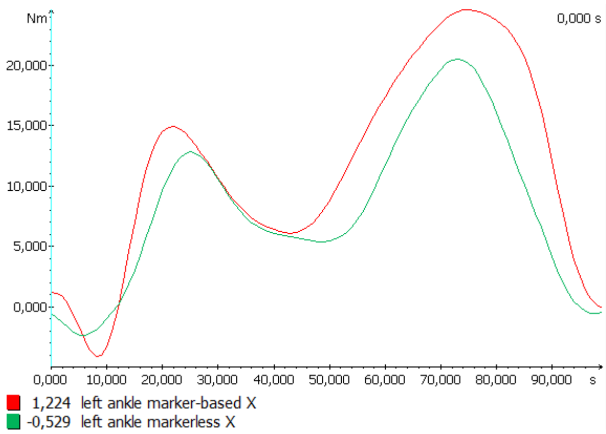

Figure 9.1: Overlay of marker-based and markerless tracked torques for the ankle supination/pronation(x-plane)

In the sagittal plane the mean correlation for the ankle plantar-/dorsalflexion is r=0.95. The highest correlation for the ankle sagittal plane is r=0.99, which is shown in figure 9.2.

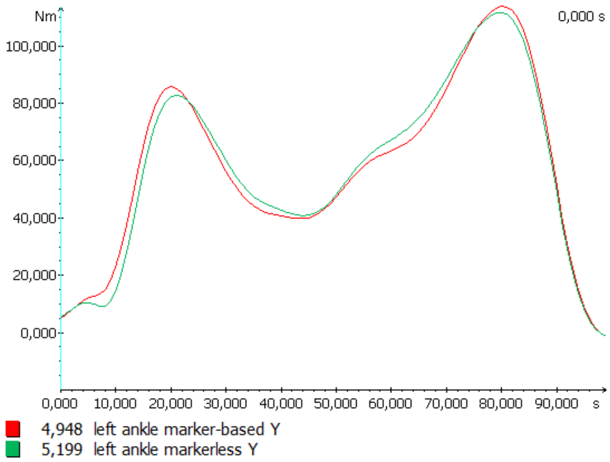

Figure 9.2: Overlay of marker-based and markerless tracked torques for the ankle plantar-/dorsalflexion (y-plane)

The mean of all correlations of the ankle in the z-plane is r=0.82, which is barley a perfect correlation.

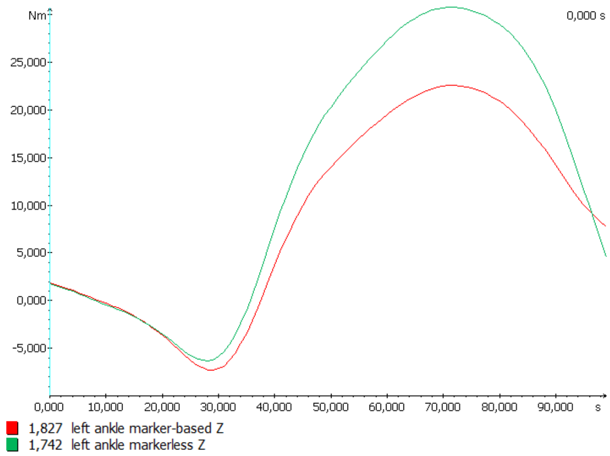

Figure 9.3: Overlay of marker-based and markerless tracked torques for the ankle inversion/eversion (z-plane)

9.2.2 Knee torques

Table 9.3: Descriptive Analysis for each movement of the knee in in all planes normalized to average person(Nm/BW*BH)

	X-Plane		Y-Plane		Z-Plane	
	Mean	SD	Mean	SD	Mean	SD
All	7.58	19.61	7.23	12.03	4.72	12.94
Decleration	2.57	28.13	4.94	12.11	5.01	15.26
Drop Jump	17.53	17.37	8.23	18.08	5.47	16.56
Lateral Shuffle	-7.15	13.74	15.24	15.38	6.25	12.67
Side Step	7.15	20.23	6,43	11.45	2.69	12.47
Triple Jump	6.77	15.31	11.53	15.64	11.36	15.47

The overall mean correlation for the ab/-adduction torque of the knee is 0.64, which is considerably good. Figure 9.4 shows an example of a perfect correlation of r=0.95.

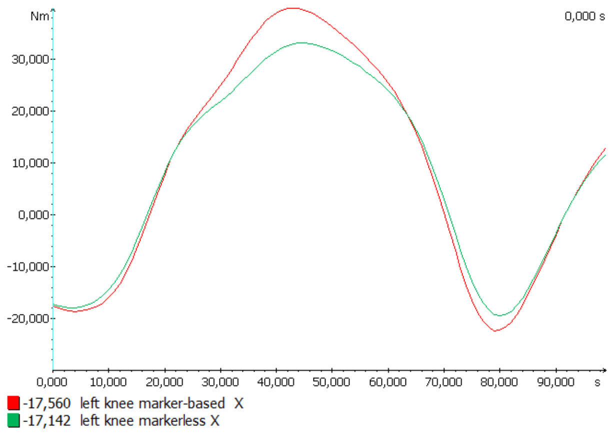

Figure 9.4: Overlay of marker-based and markerless tracked torques for the knee ab-/adduction(x-plane)

For the knee flexion/extension torque an overall mean correlation of r=0.95 is achieved. This is a perfect correlation, which is almost at r=1. Through all 25 values r=0.67 is the weakest, but can still be considered as a good correlation. Figure 9.5 shows one of the almost perfect correlations between marker-based tracking and markerless tracking.

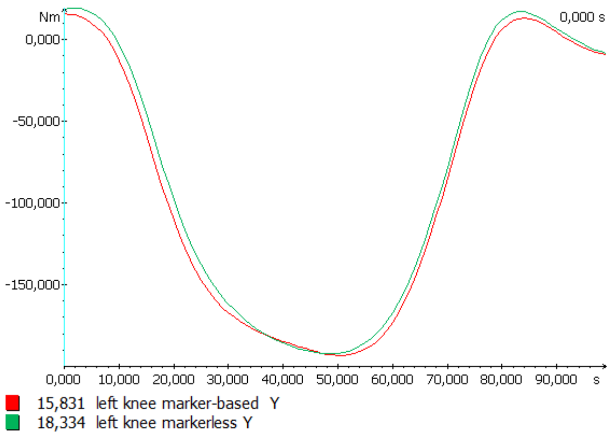

Figure 9.5: Overlay of marker-based and markerless tracked torques for the knee flexion/extension(y-plane)

The range of correlation for the internal/external rotation of the knee varies widely from 0.039 to 0.99, but proves, with a mean of 0.83 a perfect correlation in the end. Figure 9.6 pictures the perfect correlation of the internal/external rotation of the knee pictured.

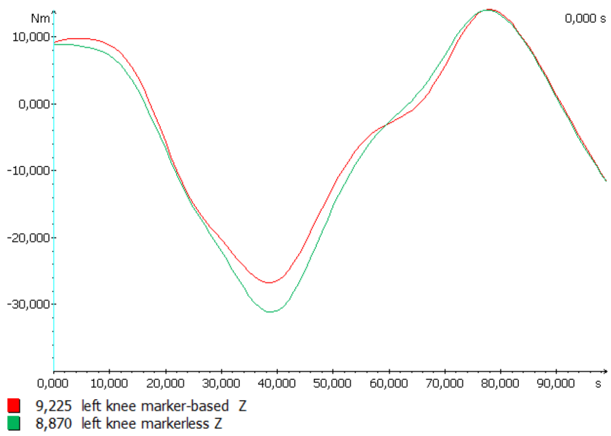

Figure 9.6: Overlay of marker-based and markerless tracked torques for the knee internal/external rotation(z-plane)

9.2.3 Hip torques

The mean correlation of the hip ab/adductor torque is at the higher border of a good correlation with r=0.78. As an example for a perfect correlation with r=0.93 see figure 9.7.

Table 9.4: Descriptive Analysis for each movement of the hip in in all planes normalized to average person(Nm/BW*BH)

	X-Plane		Y-Plane		Z-Plane	
	Mean	SD	Mean	SD	Mean	SD
All	-15.07	17.63	5.92	23.84	-9.36	22.58
Deceleration	-13.33	23.79	12.95	36.55	-15.24	23.07
Drop Jump	-12.93	18.68	-1.52	23.89	-6.18	26.03
Lateral Shuffle	-33.54	15.67	10.93	16.34	-3.38	13.07
Side Step	-13.87	17.80	7.12	25.06	-13.39	24.69
Triple Jump	-21.68	17.55	2.87	21.48	4.68	15.67

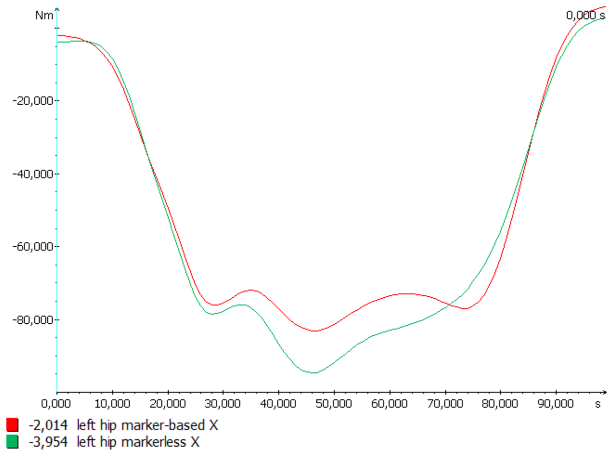

Figure 9.7: Overlay of marker-based and markerless tracked torques for the hip ab-/adduction(x-plane)

For the hip flexion/extension a perfect mean correlation of r=0.84 is achieved over all 25 items. The weakest correlation is r=0.247 and the strongest at 0.98.

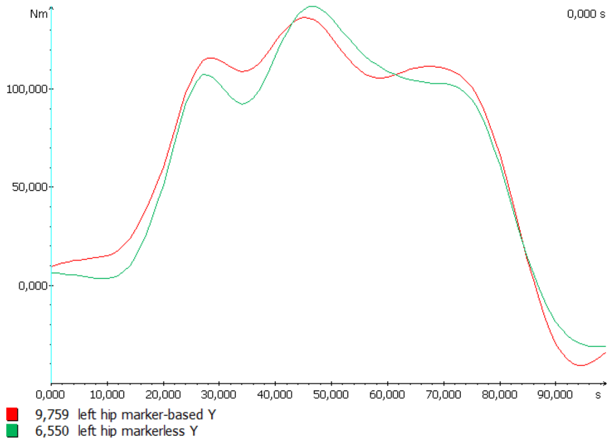

Figure 9.8: Overlay of marker-based and markerless tracked torques for the hip flexion/extension(y-plane)

The hip internal/external rotation has merely a mean correlation of 0.63. It can still be considered as moderate, but in comparison to the other mean correlation of knee and ankle, it is rather weak. Nevertheless, some of the torques show a perfect correlation between marker-based and hybrid tracking, such as figure 9.9.

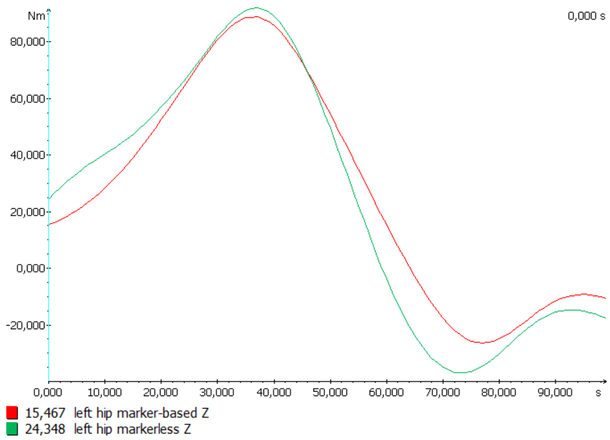

Figure 9.9: Overlay of marker-based and markerless tracked torques for the hip internal/external rotation(z-plane)

9.2.4 Lower spine

The ab-/adduction of the lower spine for markerless tracking correlates in mean with r=0.68 with marker-based tracking. This can be considered as a moderate result.

Table 9.5: Descriptive Analysis for each movement of the lower spine in in all planes normalized to average person(Nm/BW*BH)

	X-Plane		Y-Plane		Z-Plane	
	Mean	SD	Mean	SD	Mean	SD
All	-7.10	27.34	-1.36	31.34	-3.63	21.64
Deceleration	-12.12	42.36	-2.05	48.66	-2.73	36.25
Drop Jump	-1.30	21.59	-5.99	23.31	-2.00	14.74
Lateral Shuffle	-15.38	36.79	7.32	28.64	-8.20	14.63
Side Step	-7.30	26.75	-1.45	32.67	-3.16	24.57
Triple Jump	-7.02	32.77	0.40	28.19	-5.17	11.79

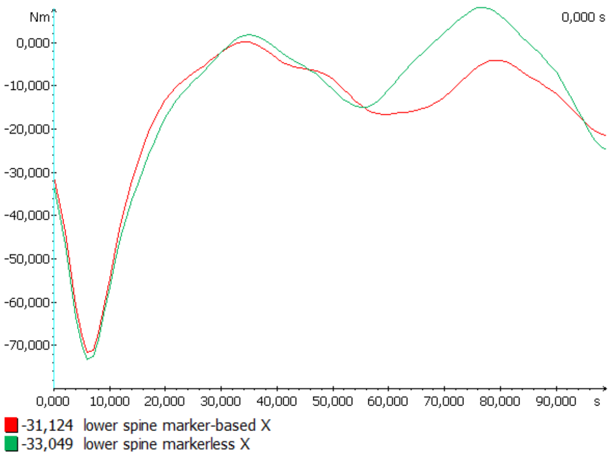

Figure 9.10: Overlay of marker-based and markerless tracked torques for the lower spine ab-/adduction(x-plane)

The flexion/extension of the lower spine shows better mean correlation with r=0.81, a result which is just within the range of perfect correlation.

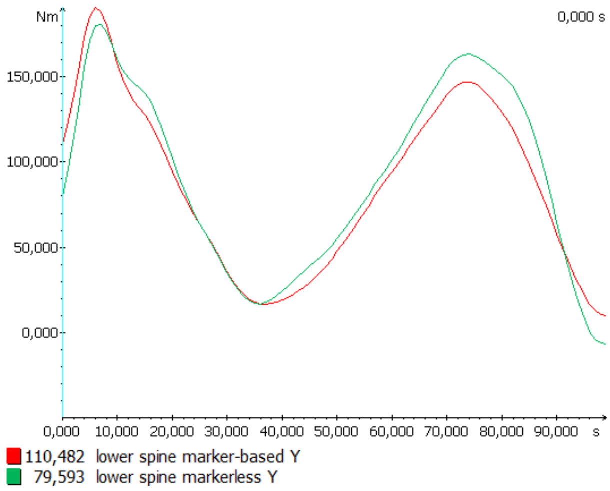

Figure 9.11: Overlay of marker-based and markerless tracked torques for the lower spine flexion/extension(y-plane)

The correlation of the lower spine rotation is in the same range as the hip rotations. With a mean of 0.65 the lower spine rotation reaches only a moderate correlation, according to table 8.1.

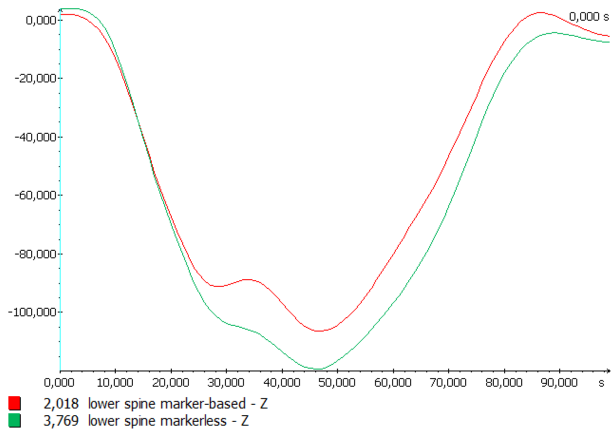

Figure 9.12: Overlay of marker-based and markerless tracked torques for the lower spine rotation(z-plane)

10 Discussion

Comparison of KAM and IRM with the return to sport scoring

There is only a weak correlation ($r_s = 0.44$, P<0.05) between the score of each movement with the combination of knee abduction moment and internal rotation moment, but it is significant. Furthermore, there is a highly significant (P<0.01) association between the knee internal rotation moment (IRM) and the return to sports scoring. This finding would emphasize the connection between increasing ACL-strain and knee abduction and internal rotation moment. [55][53][52][56][2][57] Interesting are the different forms of correlations between the movements and the total joint moment. While Lateral Shuffle has a significantly perfect positive correlation, Deceleration has a good to perfect negative correlation. Side Step and Triple Jump have only a moderate correlation. These variations could explain the overall weak correlation with a significant association. Nevertheless, overall this result does not emphasize the correlation of the scores with the KAM and the IRM. But these two moments (KAM, IRM) are only a part of the whole injury mechanism, even though an important one. In some studies [32][59] there are also significant associations between the lateral trunk lean and the knee abduction moment. These connections may have crucial influence on the correlation, if they are included. Therefore, further analysis of the joint moments related to return to sport screening scores are necessary to determine, whether these scores have an important validity. The bad correlation for Drop Jump might be caused by the fact that during a drop jump the subject lands with one leg on the ground and with the other leg on the force plate. The weight is absorbed with both legs and therefore, the obtained data is not ideal for the inverse dynamics calculation model.

Additionally, the good correlation of the single movements like Deceleration and Lateral Shuffle could have happened by chance. With only seven items for the single movements, the sample is to small and therefore not convincing enough. To investigate this association further a more complex and bigger study would have to be performed. Furthermore, the trunk lean and hip abduction moment should be involved as well.

Moment Comparison

The created marker from markerless tracking deliver good results for moments while compared to 'normally' calculated moments with 3D marker-based motion tracking. Although the overall correlations are very good, there are some outlier with no correlation at all. Additionally, ankle values for the x-planes represent the worst result from this analysis with only $r_s = 0.36$. The reason for that could be the not perfectly light setup, which might cause a shadow from the lower leg and therefore cause irritation for the background subtraction. A perfect adjustment is then hard to obtain.

The other frontal moments like knee ($r_s = 0.64$), hip ($r_s = 0.78$) and lower spine ($r_s = 0.68$) ab-/adduction show a good correlation between the two tracking methods. But the standard deviation of the difference is up to 27 Nm (for lower spine).

The hip and trunk rotational moments (transverse plane) have a moderate correlation ($r_s = 0.63$ and $r_s = 0.65$). This is referable to the already mentioned difficulties during the model adjustment for the pelvis. The model cannot really draw the line between hip and trunk and increases the difficulty to fit the model perfectly in the silhouette. Furthermore, during the tracking process Shape adjusts the model up to 15 times in each frame. This could cause a more obvious movement of the pelvis, even when the subjects pelvis does not move.

Moments in the sagittal plane match the best with a correlation range from 0.81 to 0.95 over all joints. The movements in the sagittal plane have a bigger range of motion and are easier to detect. Furthermore, the Shape version used in this work only provides a hinge joint for the knee and cannot track abduction and adduction not to mention rotational movement. This affects the ankle transverse and the rotational movements as well. The current released version (Version 3.0) provides a ball joint for the knee, which is limited in the different directions. Nevertheless, even for rotational moment the correlation is $r_s = 0.83$ and for abduction/addcution moment $r_s = 0.64$. This might be caused by the fact, that the kinetic and kinematic data is not calculated with Shape, but with Simi Motion a different calculation algorithm is used and therefore transverse and frontal moments can be calculated. Aside from that the calculations are not based on the silhouette but rather on the virtually created marker.
But regardless of the good correlation in the sagittal plane, the mean difference between marker-based and markerless moments still ranges from 1.36 Nm (SD=31.3) to 11.6 Nm (SD=11.2). The difference of approximately 12 Nm and a deviation up to 31 Nm is very high and can be crucial in the distinction between for example an abduction or an adduction moment.

The marker in Shape are aligned at the model and because the model cannot be aligned 100 percent perfectly to the silhouette of the subject, there is a difference between the real and the virtual markers. This effects movements with smaller ranges of motion more than movements with bigger ones. A solution for this problem is already shown in part I of this work: Hybrid tracking. This combination stabilizes body parts (e.g. the pelvis), which occur to be very difficult to adjust. Furthermore, segmentation problems can lead to this effect as well because due to segmentation errors the silhouettes appear to be bigger than the body segments really are. Thus, bigger movements of segments within

their silhouettes can occur.
Another reason for the difference could be the fact that angles smaller than 5° are hard to match.[18] The reason is that the Shape model is always able to move very slightly within the silhouette as a 100 percent alignment between model and silhouette is not reached. The positions of the segments of the Shape model during tracking are optimized for each frame which always means some kind of small movement of the model within the silhouette.

11 Conclusion and outlook to further possibilities of investigation

In this part of the work we were able to show that there are significant associations between knee abduction moment and internal rotation moment and the return to sport scoring. The investigation does not have a large sample size, but it can be considered as a first glimpse on this topic. The different correlations of the movements should be investigated further to gain a more precise look on the injury-causing moments and movements. Additionally, more factors should be taken into account such as lateral trunk lean and hip flexion.[32][59] These seem to influence the strain in the ACL as well. The right associations between all those factors need to be found to generate an unifying return to sport screening. With such a study a better return to sport screening could be build.

The comparison of the moments between markerless and marker-based tracking are a double-edged sword. On one side the correlations are favorable, which means the movement and the detection of the movement are similar. This shows that there is not much difference between these two methods. On the other side the differences between these methods have high standard deviations in almost all planes. This leads to the conclusion that a inter-subject comparison is difficult, but a intra-subject comparison, for example before and after a treatment, is feasible and supports the usage of markerless tracking.

There is also another possibility to gain kinetic data. An earlier work on a similar approach [60] has demonstrated that with a musculoskeletal simulation from AnyBody[4] ground reaction forces are predictable by using markerless silhouette-based tracking. The results between marker-based tracking and markerless tracking showed very good correlations.

Concluding out of theses results, markerless tracking proves again to be a good alternative for the clinical application of return to sport screenings. The possibility to track kinetic data could open the door to obtain even more data about the ACL injury mechanism. It is important to investigate the mechanisms of ACL injury to get on the same page in the field of rehabilitation. Markerless tracking with Simi Shape would be a preferable technology to answer this question properly. More data could be collected easily and more often. Not only research institutes, which perform large studies, also more clinical-orientated institutes could collect and merge this kind of data.

Further research will show, whether markerless tracking could consolidate its stand in the clinical application.

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Appendix

A Survey about marker placement

Detailed results of the survey about marker placement are presented in table A.1. Participants were asked how many markers they usually place, which marker set they use and how much time they need for marker placement. [18]

Table A.1: Results of the survey about marker placement

Respondent	Number of markers	Placement	Time [min]
1	20	Hanavan marker set (full body)	10-15
2	27	Marker set for lower extremities	20-30
3	29	LAMB model (full body)	30
4	30	Helen Hayes marker set +additional markers	15
5	40	Plug-in-Gait (full body)	10
6	40	Plug-in-Gait (full body)	10-15

B Point of time for the measurement

The point of times for each subject and each movement at the lowest point of the center of mass are presented in table B.1.

Table B.1: Times for the lowest point of the COM [s]

Subject	Deceleration	Drop Jump	Lateral Shuffle	Side Step	Step Down	Triple Jump
1	2.1390	15.69	8.96	19.82	4.459	16.56
2	11.256	17.549	4.39	3.928	5.722	19.95
3	17.39	17.969	3.164	2.945	8.665	24.9
4	3.834	15.488	3.13	14.932	23.064	9.573
5	7.43	2.509	9.174	10.577	10.247	7.784
6	10.268	2.065	6.335	13.441	12.57	12.323
7	16.718	19.451	10.079	17.141	14.507	14.217
8	14.887	17.315	2.791	12.42	18.532	21.061

C Obtained data for RTS scoring and moment analysis

C.1 Scorings

Return to sports scoring for marker-based, rater-based, markerless and Hybrid tracking for each subject and each movement.

Table C.1: Scoring for marker-based tracking

Subject	Marker	Deceleration	Drop Jump	Lateral Shuffle	Step Down	Triple Jump	Final Score
1	8	3	5	5	4	7	32
2	8	4	3	5	2	6	28
3	8	4	6	8	6	6	39
4	8	1	3	6	6	6	30
5	9	5	3	5	4	6	32
6	10	5	4	4	5	9	37
7	7	3	5	7	5	7	34
8	9	4	4	8	1	4	30

Table C.2: Scoring for rater-based tracking

Subject	Deceleration	Drop Jump	Lateral Shuffle	Step Down	Side Cut	Triple Jump	Final Score
1	8	5	5	6	6	8	38
2	9	5	6	5	7	9	41
3	8	3	5	6	5	5	32
4	8	4	3	2	7	7	31
5	9	5	4	4	6	6	34
6	8	4	6	5	9	7	39
7	9	5	4	4	3	9	34
8	10	4	3	1	7	4	29

Table C.3: Scoring for markerless tracking

Subject	Deceleration	Drop Jump	Lateral Shuffle	Step Down	Side Cut	Triple Jump	Final Score
1	9	5	4	5	4	8	35
2	8	4	3	6	5	6	32
3	8	5	5	7	6	7	38
4	8	1	4	5	6	5	29
5	8	5	3	6	3	4	29
6	10	4	4	4	6	9	37
7	7	4	6	9	5	6	37
8	9	4	4	9	2	5	33

Table C.4: Scoring for Hybrid tracking

Subject	Deceleration	Drop Jump	Lateral Shuffle	Step Down	Side Cut	Triple Jump	Final Score
1	9	5	5	5	5	8	37
2	7	4	4	6	4	5	30
3	8	4	5	8	6	7	38
4	8	2	3	6	5	6	30
5	8	4	3	6	4	4	29
6	10	5	4	6	5	9	39
7	7	3	5	8	5	7	35
8	9	4	5	8	1	5	32

C.2 Knee abduction moment and internal rotation moment

The knee abduction moment and the internal rotation moment are taken from the lowest point of the COM. Each moment is first normalized to body height and body weight and then normalized to a average person with 75 Kg and 1.75m. "Total" means the addition of knee abduction moment and internal rotation moment.

Subject	Movement	Knee abduction Moment	Internal Rotation	Total	RTS Score
2	Deceleration	29,922	58,096	88,018	8
3	Deceleration	29,741	53,076	82,817	8
4	Deceleration	-3,770	31,428	27,658	8
5	Deceleration	19,470	25,904	45,374	9
6	Deceleration	-5,152	22,394	17,242	10
7	Deceleration	86,481	30,896	117,377	7
8	Deceleration	4,057	11,851	15,909	9
2	Drop Jump	-12,630	9,076	-3,554	4
3	Drop Jump	9,702	8,606	18,308	4
4	Drop Jump	-27,001	-30,981	-57,982	1
5	Drop Jump	4,266	-2,052	2,214	5
6	Drop Jump	4,133	-8,085	-3,952	5
7	Drop Jump	21,801	-5,409	16,391	3
8	Drop Jump	-0,206	-20,949	-21,155	4
2	Lateral Shuffle	12,028	6,868	18,896	3
3	Lateral Shuffle	111,874	65,168	177,043	6
4	Lateral Shuffle	16,741	25,513	42,255	3
5	Lateral Shuffle	-26,146	-1,472	-27,618	3
6	Lateral Shuffle	8,275	45,660	53,935	4
7	Lateral Shuffle	61,907	45,165	107,072	5
8	Lateral Shuffle	41,618	56,955	98,573	4
2	Side Cut	24,939	10,920	35,859	5
3	Side Cut	43,759	10,686	54,445	8
4	Side Cut	3,562	-0,737	2,825	6
5	Side Cut	21,510	35,125	56,635	5
6	Side Cut	-45,505	-2,691	-48,196	4
7	Side Cut	43,677	108,951	152,629	7
2	Triple jump	13,048	31,559	44,608	6
3	Triple jump	23,738	46,213	69,950	7
4	Triple jump	-15,351	31,645	16,293	6
5	Triple jump	1,260	33,492	34,752	6
6	Triple jump	-2,504	35,265	32,761	9
7	Triple jump	42,539	16,080	58,619	7
8	Triple Jump	6,671	2,355	9,027	4

C.3 Moments descriptive statistics

The next pages show the different mean values of the difference from markerless and marker-based moments. They are sorted by the movements. For every joint each plane is listed with mean difference and the standard deviation. The values are already normalized to body weight and body height. In the last rows the moments are normalized to an average person with a weight of 75 Kg and height of 1.75m.

Subject	Movement	Ankle X		Ankle Y	
		Difference	***SD***	**Difference**	***SD***
2	Deceleration	0,01	*0,05*	-0,09	*0,07*
3	Deceleration	-0,04	*0,04*	-0,09	*0,09*
4	Deceleration	0,01	*0,04*	-0,12	*0,12*
5	Deceleration	0,00	*0,00*	-0,04	*-0,04*
6	Deceleration	0,03	*0,05*	0,00	*0,04*
7	Deceleration	-0,12	*0,07*	-0,26	*0,08*
2	Drop Jump	0,11	*0,11*	-0,04	*0,06*
3	Drop Jump	0,16	*0,13*	0,06	*0,09*
4	Drop Jump	0,03	*0,05*	-0,15	*0,06*
6	Drop Jump	0,06	*0,05*	0,13	*0,03*
7	Drop Jump	-0,26	*0,04*	-0,19	*0,04*
2	Lateral Shuffle	0,11	*0,09*	-0,07	*0,05*
3	Lateral Shuffle	0,07	*0,09*	-0,10	*0,10*
4	Lateral Shuffle	-0,01	*0,04*	-0,16	*0,09*
6	Lateral Shuffle	0,34	*0,18*	-0,12	*0,10*
7	Lateral Shuffle	-0,16	*0,11*	-0,21	*0,03*
2	Side Step	0,02	*0,05*	-0,04	*0,06*
4	Side Step	-0,02	*0,07*	-0,22	*0,08*
6	Side Step	-0,01	*0,09*	0,11	*0,10*
7	Side Step	-0,10	*0,12*	-0,10	*0,12*
2	Triple Jump	0,06	*0,05*	-0,31	*0,34*
3	Triple Jump	-0,10	*0,05*	0,10	*0,14*
4	Triple Jump	0,03	*0,07*	-0,25	*0,13*
6	Triple Jump	-0,04	*0,19*	0,04	*0,13*
7	Triple Jump	-0,23	*0,04*	-0,11	*0,03*

	Normalized /BW*BH				
	All	**0,00**	***0,07***	**-0,09**	***0,09***
	Deceleration	-0,02	*0,04*	-0,10	*0,06*
	Drop Jump	0,02	*0,08*	-0,03	*0,05*
	Lateral Shuffle	0,07	*0,10*	-0,13	*0,07*
	Side Step	-0,03	*0,08*	-0,06	*0,09*
	Triple Jump	-0,06	*0,08*	-0,11	*0,15*

	Average 75Kg 1,75m				
	All	**-0,32**	**9,73**	**-11,63**	**11,22**
	Deceleration	8,06	12,42	-15,34	9,49
	Drop Jump	-4,66	9,77	-11,04	20,27
	Lateral Shuffle	-7,86	12,02	-13,40	12,53
	Side Step	1,35	9,87	-10,79	9,16
	Triple Jump	-7,29	10,27	-13,99	20,26

Subject	Movement	Ankle Z		Knee X	
		Difference	*SD*	Difference	*SD*
2	Deceleration	-0,04	*0,03*	0,36	*0,25*
3	Deceleration	-0,06	*0,05*	0,24	*0,22*
4	Deceleration	0,02	*0,03*	-0,14	*0,15*
5	Deceleration	-0,05	*-0,05*	0,36	*0,36*
6	Deceleration	-0,03	*0,03*	0,15	*0,11*
7	Deceleration	0,00	*0,01*	-0,09	*0,10*
2	Drop Jump	0,00	*0,04*	-0,11	*0,08*
3	Drop Jump	0,00	*0,02*	0,02	*0,05*
4	Drop Jump	0,01	*0,03*	0,19	*0,10*
6	Drop Jump	-0,07	*0,01*	-0,03	*0,06*
7	Drop Jump	0,04	*0,03*	-0,01	*0,05*
2	Lateral Shuffle	-0,03	*0,02*	0,04	*0,16*
3	Lateral Shuffle	-0,05	*0,04*	0,13	*0,20*
4	Lateral Shuffle	0,01	*0,02*	-0,13	*0,16*
6	Lateral Shuffle	-0,03	*0,03*	0,18	*0,34*
7	Lateral Shuffle	-0,02	*0,02*	-0,17	*0,26*
2	Side Step	-0,03	*0,03*	0,07	*0,16*
4	Side Step	0,01	*0,03*	-0,10	*0,08*
6	Side Step	-0,08	*0,04*	0,10	*0,11*
7	Side Step	-0,01	*0,01*	0,13	*0,16*
2	Triple Jump	-0,03	*0,02*	0,14	*0,11*
3	Triple Jump	-0,10	*0,05*	0,39	*0,20*
4	Triple Jump	0,04	*0,02*	-0,18	*0,10*
6	Triple Jump	-0,08	*0,05*	0,14	*0,12*
7	Triple Jump	0,01	*0,01*	-0,24	*0,05*

	Normalized /BW*BH				
	All	**-0,02**	***0,02***	**0,06**	***0,15***
	Deceleration	-0,03	*0,02*	0,15	*0,20*
	Drop Jump	0,00	*0,02*	0,01	*0,07*
	Lateral Shuffle	-0,02	*0,03*	0,01	*0,22*
	Side Step	-0,03	*0,03*	0,05	*0,13*
	Triple Jump	-0,03	*0,03*	0,05	*0,12*

	Average 75Kg 1,75m				
	All	**-2,96**	**3,16**	**7,58**	**19,61**
	Deceleration	-3,17	3,49	2,57	28,13
	Drop Jump	-5,81	3,92	17,53	17,37
	Lateral Shuffle	-1,85	3,36	-7,15	13,74
	Side Step	-2,60	3,04	7,15	20,23
	Triple Jump	-4,49	3,93	6,77	15,31

Subject	Movement	Knee Y		Knee Z	
		Difference	***SD***	**Difference**	***SD***
2	Deceleration	-0,04	*0,03*	0,03	*0,11*
3	Deceleration	0,04	*0,07*	0,05	*0,07*
4	Deceleration	0,10	*0,11*	-0,05	*0,04*
5	Deceleration	-0,05	*-0,05*	0,05	*0,05*
6	Deceleration	-0,04	*0,24*	0,19	*0,18*
7	Deceleration	0,07	*0,04*	-0,01	*0,05*
2	Drop Jump	-0,02	*0,03*	0,05	*0,06*
3	Drop Jump	0,03	*0,04*	0,01	*0,07*
4	Drop Jump	0,08	*0,07*	-0,10	*0,06*
6	Drop Jump	0,17	*0,04*	0,08	*0,03*
7	Drop Jump	0,09	*0,05*	-0,01	*0,13*
2	Lateral Shuffle	-0,05	*0,04*	0,04	*0,04*
3	Lateral Shuffle	0,01	*0,03*	-0,04	*0,04*
4	Lateral Shuffle	0,11	*0,20*	-0,02	*0,24*
6	Lateral Shuffle	0,19	*0,15*	0,05	*0,14*
7	Lateral Shuffle	0,03	*0,11*	0,17	*0,13*
2	Side Step	-0,06	*0,03*	0,03	*0,10*
4	Side Step	0,10	*0,14*	-0,12	*0,06*
6	Side Step	0,17	*0,23*	0,07	*0,17*
7	Side Step	0,01	*0,10*	-0,02	*0,10*
2	Triple Jump	-0,01	*0,06*	0,31	*0,22*
3	Triple Jump	0,04	*0,16*	-0,03	*0,08*
4	Triple Jump	0,15	*0,12*	-0,07	*0,08*
6	Triple Jump	0,19	*0,20*	0,23	*0,17*
7	Triple Jump	0,06	*0,06*	-0,01	*0,04*

	Normalized /BW*BH				
	All	**0,06**	***0,09***	**0,04**	***0,10***
	Deceleration	0,01	*0,07*	0,05	*0,08*
	Drop Jump	0,07	*0,05*	0,01	*0,07*
	Lateral Shuffle	0,06	*0,11*	0,04	*0,12*
	Side Step	0,06	*0,12*	-0,01	*0,11*
	Triple Jump	0,09	*0,12*	0,09	*0,12*

	Average 75Kg 1,75m				
	All	**7,23**	**12,03**	**4,72**	**12,94**
	Deceleration	4,94	12,11	5,01	15,26
	Drop Jump	8,23	18,08	5,47	16,56
	Lateral Shuffle	15,24	15,38	6,25	12,67
	Side Step	6,43	11,45	2,69	12,47
	Triple Jump	11,53	15,64	11,36	15,47

Subject	Movement	Hip X		Hip Y	
		Difference	***SD***	**Difference**	***SD***
2	Deceleration	-0,03	*0,07*	0,01	*0,18*
3	Deceleration	0,08	*0,08*	0,04	*0,06*
4	Deceleration	-0,11	*0,09*	0,10	*0,09*
5	Deceleration	0,12	*0,12*	0,00	*0,00*
6	Deceleration	-0,19	*0,12*	-0,05	*0,09*
7	Deceleration	-0,28	*0,06*	0,03	*0,05*
2	Drop Jump	0,02	*0,05*	0,02	*0,09*
3	Drop Jump	0,06	*0,10*	0,02	*0,08*
4	Drop Jump	-0,12	*0,21*	0,24	*0,22*
6	Drop Jump	-0,34	*0,09*	-0,14	*0,13*
7	Drop Jump	-0,07	*0,22*	0,04	*0,65*
2	Lateral Shuffle	0,02	*0,05*	0,11	*0,08*
3	Lateral Shuffle	0,10	*0,08*	0,07	*0,14*
4	Lateral Shuffle	-0,07	*0,48*	0,22	*0,42*
6	Lateral Shuffle	-0,17	*0,13*	-0,23	*0,18*
7	Lateral Shuffle	-0,51	*0,28*	0,19	*0,56*
2	Side Step	0,03	*0,06*	0,23	*0,29*
4	Side Step	-0,23	*0,14*	0,29	*0,14*
6	Side Step	-0,25	*0,06*	-0,22	*0,12*
7	Side Step	-0,10	*0,18*	0,05	*0,15*
2	Triple Jump	-0,07	*0,15*	-0,22	*0,45*
3	Triple Jump	0,15	*0,18*	0,04	*0,06*
4	Triple Jump	-0,19	*0,13*	0,18	*0,18*
6	Triple Jump	-0,23	*0,11*	-0,06	*0,09*
7	Triple Jump	-0,49	*0,10*	0,16	*0,05*
	Normalized /BW*BH				
	All	**-0,11**	***0,13***	**0,05**	***0,18***
	Deceleration	-0,07	*0,09*	0,02	*0,08*
	Drop Jump	-0,09	*0,14*	0,04	*0,23*
	Lateral Shuffle	-0,13	*0,20*	0,07	*0,28*
	Side Step	-0,14	*0,11*	0,09	*0,17*
	Triple Jump	-0,17	*0,13*	0,02	*0,16*
	Average 75Kg 1,75m				
	All	**-15,07**	**17,63**	**5,92**	**23,84**
	Deceleration	-13,33	23,79	12,95	36,55
	Drop Jump	-12,93	18,68	-1,52	23,89
	Lateral Shuffle	-33,54	15,67	10,93	16,34
	Side Step	-13,87	17,80	7,12	25,06
	Triple Jump	-21,68	17,55	2,87	21,48

Subject	Movement	Hip Z		Lower X	
		Difference	***SD***	**Difference**	***SD***
2	Deceleration	0,02	0,16	0,17	*0,15*
3	Deceleration	-0,02	*0,08*	0,00	*0,07*
4	Deceleration	-0,02	*0,06*	-0,01	*0,09*
5	Deceleration	0,09	*0,09*	-0,19	*-0,19*
6	Deceleration	-0,15	*0,26*	-0,02	*0,06*
7	Deceleration	-0,10	*0,07*	-0,08	*0,05*
2	Drop Jump	-0,11	*0,15*	-0,06	*0,08*
3	Drop Jump	-0,15	*0,18*	-0,01	*0,08*
4	Drop Jump	0,00	*0,05*	-0,03	*0,14*
6	Drop Jump	-0,21	*0,05*	-0,03	*0,13*
7	Drop Jump	-0,17	*0,88*	-0,06	*0,88*
2	Lateral Shuffle	-0,28	*0,17*	-0,20	*0,24*
3	Lateral Shuffle	-0,08	*0,06*	0,01	*0,08*
4	Lateral Shuffle	-0,03	*0,25*	-0,03	*0,58*
6	Lateral Shuffle	-0,12	*0,14*	0,03	*0,11*
7	Lateral Shuffle	-0,20	*0,35*	-0,37	*0,80*
2	Side Step	0,01	*0,09*	0,00	*0,13*
4	Side Step	-0,06	*0,08*	-0,12	*0,16*
6	Side Step	-0,25	*0,31*	0,06	*0,09*
7	Side Step	-0,14	*0,23*	-0,13	*0,23*
2	Triple Jump	0,03	*0,14*	0,14	*0,21*
3	Triple Jump	0,18	*0,23*	0,00	*0,12*
4	Triple Jump	-0,07	*0,09*	-0,08	*0,72*
6	Triple Jump	0,08	*0,09*	-0,08	*0,09*
7	Triple Jump	-0,03	*0,05*	-0,26	*0,10*

	Normalized /BW*BH				
	All	**-0,07**	***0,17***	**-0,05**	***0,21***
	Deceleration	-0,03	*0,12*	-0,02	*0,04*
	Drop Jump	-0,13	*0,26*	-0,04	*0,26*
	Lateral Shuffle	-0,14	*0,19*	-0,11	*0,36*
	Side Step	-0,11	*0,18*	-0,05	*0,15*
	Triple Jump	0,04	*0,12*	-0,05	*0,25*

	Average 75Kg 1,75m				
	All	**-9,36**	**22,58**	**-7,10**	**27,34**
	Deceleration	-15,24	23,07	-12,12	42,36
	Drop Jump	-6,18	26,03	-1,30	21,59
	Lateral Shuffle	-3,38	13,07	-15,38	36,79
	Side Step	-13,39	24,69	-7,30	26,75
	Triple Jump	4,68	15,67	-7,02	32,77

Subject	Movement	Lower Y		Lower Z	
		Difference	***SD***	**Difference**	***SD***
2	Deceleration	-0,04	*0,29*	0,05	*0,08*
3	Deceleration	-0,01	*0,10*	0,03	*0,05*
4	Deceleration	0,03	*0,07*	-0,05	*0,09*
5	Deceleration	-0,10	*-0,10*	0,02	*0,02*
6	Deceleration	-0,05	*0,12*	-0,01	*0,05*
7	Deceleration	0,05	*0,05*	-0,15	*0,06*
2	Drop Jump	0,06	*0,11*	0,06	*0,05*
3	Drop Jump	0,00	*0,12*	-0,05	*0,10*
4	Drop Jump	-0,07	*0,14*	-0,07	*0,07*
6	Drop Jump	-0,11	*0,08*	0,00	*0,07*
7	Drop Jump	0,08	*1,24*	-0,10	*0,97*
2	Lateral Shuffle	-0,30	*0,18*	0,08	*0,12*
3	Lateral Shuffle	0,04	*0,16*	-0,02	*0,07*
4	Lateral Shuffle	0,07	*0,77*	-0,05	*0,62*
6	Lateral Shuffle	-0,16	*0,16*	-0,04	*0,06*
7	Lateral Shuffle	0,12	*0,72*	-0,17	*0,65*
2	Side Step	0,13	*0,23*	0,08	*0,13*
4	Side Step	0,07	*0,15*	-0,11	*0,09*
6	Side Step	-0,14	*0,14*	0,03	*0,14*
7	Side Step	0,06	*0,15*	-0,03	*0,16*
2	Triple Jump	-0,20	*0,35*	0,02	*0,09*
3	Triple Jump	-0,01	*0,09*	0,01	*0,08*
4	Triple Jump	0,12	*0,39*	-0,04	*0,12*
6	Triple Jump	-0,04	*0,18*	-0,04	*0,11*
7	Triple Jump	0,15	*0,06*	-0,14	*0,05*
	Normalized /BW*BH				
	All	**-0,01**	***0,24***	**-0,03**	*0,16*
	Deceleration	-0,02	*0,09*	-0,02	*0,06*
	Drop Jump	-0,01	*0,34*	-0,03	*0,25*
	Lateral Shuffle	-0,04	*0,40*	-0,04	*0,30*
	Side Step	0,03	*0,17*	-0,01	*0,13*
	Triple Jump	0,00	*0,21*	-0,04	*0,09*
	Average 75Kg 1,75m				
	All	**-1,36**	**31,34**	**-3,63**	**21,64**
	Deceleration	-2,05	48,66	-2,73	36,25
	Drop Jump	-5,99	23,31	-2,00	14,74
	Lateral Shuffle	7,32	28,64	-8,20	14,63
	Side Step	-1,45	32,67	-3,16	24,57
	Triple Jump	0,40	28,19	-5,17	11,79

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