Development of Algorithms for Computing Knee Stability Parameters Using a Sensor Equipped Knee Sleeve

Master's Thesis in Medical Engineering

submitted
by

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Übersicht

Ein stabiles Knie ist im Sport und auch im Alltag von großer Bedeutung. Ein Mangel an Stabilität kann Verletzungen, wie Bänderrisse, induzieren und zum Ende der Karriere eines Profisportlers führen. Basierend auf Literaturrecherchen werden in dieser Arbeit verschiedene Risikofaktoren für ein instabiles Knie vorgestellt und eine Testbatterie zur Erhöhung und Analyse der Stabilisierung zusammengestellt. Diese Testbatterie besteht aus verschiedenen Übungen, einschließlich Balance-, Kraft- und Sprungtests. Da nicht immer ein Physiotherapeut zur Beurteilung der Kniestabilität vor Ort ist, besteht die Nachfrage nach einer Trainingshilfe, die ein automatisiertes Feedback liefert. Zu diesem Zweck wurde eine, mit Sensoren ausgestattete, Kniebandage verwendet. Diese enthält zwei inertiale Messeinheiten, die Beschleunigungs- und Winkelgeschwindigkeitsdaten aufnehmen und anhand derer die vordefinierten Parameter analysiert werden können, um dem Benutzer eine Rückmeldung zu geben.

Im Rahmen dieser Masterarbeit wurden Algorithmen entwickelt, die auf einem Subsequence Dynamic Time Warping (SDTW) Ansatz basieren. Die Algorithmen extrahieren und analysieren Parameter, wie Sprunghöhe und Ereigniserkennung, basierend auf den Sensordaten der Kniebandage. Um die Genauigkeit der entwickelten Algorithmen auf die Testbatterie zu bewerten, wurde eine Studie mit 16 gesunden Probanden durchgeführt. Eine Kraftmessplatte und ein Motion Capture System dienten als Referenzsysteme. Die Sprunghöhe wurde nach der Flugzeitmethode berechnet und mit den Daten der Kraftmessplatte verglichen. Hierbei beträgt der mittlere absolute Fehler für Drop Jumps 2.1 cm, für Squat Jumps 4.1 cm und für einbeinige Squat Jumps 3.5 cm (rechts) bzw. 3.7 cm (links). Die Sensitivität für die Erkennung von Glute Bridge Übungen und Kniebeugen liegt im Bereich von 96.6- 98.6 % und die Sensitivität bei Einbeinsprüngen ist 91.0-99.2 %. Darüber hinaus analysierten biomechanische Experten Videos der durchgeführten Sprünge und bewerteten die Absprung- und Landephasen. Die Erwartungen wurden erfüllt und zeigten eine Korrelation zwischen qualitativen und quantitativen Ergebnissen.

Abstract

A stable knee is of great importance in sport and everyday life. Lack of stability can cause injuries like ligament ruptures and may result in the end of a professional's career. Based on literature research several risk factors for an unstable knee are presented in this work and a test battery is composed to increase and analyze stabilization. This test battery consists of several exercises including balance, strength and jump tests. As there is not always a physiotherapist nearby to determine the knee stability, there is a demand for a training aid to get an automated feedback. To this end, an existing sensor equipped knee sleeve has been used. It contains two inertial sensors recording acceleration and angular velocity data which were analyzed for predefined parameters to give feedback to the user.

In this master thesis algorithms based on a subsequence dynamic time warping (SDTW) approach will be developed. The algorithms extract and evaluate parameters, such as jump height and event detection, based on data acquired by the knee sleeve. A study with 16 healthy subjects has been conducted to evaluate the accuracy of the developed algorithms on the test battery. As reference systems a force plate and also a motion capturing system were used. The jump height was calculated using the flight-time-method and hereby compared to the force plate data. The mean absolute error for drop jumps is 2.1 cm, squat jumps 4.1 cm and for single leg squat jumps 3.5 cm (right) and 3.7 cm (left). The sensitivity for detecting glute bridges and squats ranges from 96.6-98.6 % while the sensitivity for single leg hops is 91.0-99.2 %. Furthermore, biomechanical experts evaluated videos of the performed jumps and rated the take-off and landing phases. The expectations were met and showed a correlation between qualitative and quantitative results.

Contents

Chapter 1

Introduction

The anterior cruciate ligament (ACL) is of great importance to the kinematic function of the knee joint. The rupture of the ACL is one of the most common knee injuries and means serious consequences for the affected person. It leads not only to pain and to long rehabilitation phases but also results in the end of a professional's career. Beside the impairment of chronic instabilities also recurrent subluxation events cause meniscus and cartilage damage [DF15]. The incidence of osteoarthritis is significantly increased in athletes with a rupture of the ACL [DF15, Nes17]. Injuries like the ACL rupture can occur during training and matches without any contact and are often caused by an unstable knee. The therapy and rehabilitation of injuries will not be emphasized in this thesis, but rather the prevention methods and the detection of risk factors to develop preventive measures and targeted training.

Motivation To prevent the athletes from injuries, there are several training exercises and strength test batteries to evaluate and strengthen the knee stability. Several studies confirm the fundamental importance of prevention programs for ACL ruptures. Kiani et al. [Kia10] associated a 77 % reduction of soccer related knee injury incidence in teenage girls due to a prevention program. Especially the non-contact knee injury incidence rate was 90 % lower in the intervention group. Further studies follow up with prevention programs and also gained numbers of injury reduction. This leads to a rethinking of training plans and an extension with preventive exercises. Apart from subjective data like pain or occurrence of giving way, there are also measurable parameters that describe the knee stability. There are different patterns of knee instability where the ACL is involved. Besides valgus (medial) and varus (lateral) movements there are also rotatory instabilities (anteromedial and anterolateral)

[Suk11]. Knowing these parameters can help to minimize the risk for an ACL rupture and to prevent the athlete from injuries. In the beginning of prevention an elucidation of mechanisms of injuries and movement patterns is necessary to increase the athletes motivation to invest time on a prevention program. Such a program is suitable for everybody who needs to stabilize his knee to prevent (re-)injury, to reduce pain or who has a risk for an anterior cruciate ligament rupture. As there is not always a physiotherapist nearby to determine the knee stability, there is a demand for a training aid to get an automated feedback. An aid like this can help to stabilize the knee, to prevent (re-)injuries and to offer a save return to previous activity levels in case of knee related problems. Usually, biomechanical analysis are performed and evaluated using motion capturing systems and force plates. A motion capturing system provides a precise measurement of movement patterns of athletes with good resolution and a large number of parameters such as joint angles, forces and motion tracking. However, it is not suitable for daily use as it is not available for amateur athletes. Force plates are expensive and barely portable and a flat surface is necessary to use them. Due to this, it is not possible to train outside or in a different surrounding. A sensor equipped sleeve may overcome these limitations. It can easily be taken to different training spots to perform private training lessons as it is portable and affordable. Two knee sleeves, developed in a joint cooperation (project of adidas® AG and Otto Bock HealthCare GmbH) by Maurer et al. [Mau17], were used in this thesis. They include two integrated inertial measurement units (IMUs) and are suitable for this topic as IMUs offer a new opportunity for in-field diagnosis [Jai14]. The sleeve is a wireless, wearable device for motion analysis, allowing the athlete to move freely in any environment. The embedded IMU sensors offer triaxial acceleration and angular velocity data which are used to analyze and evaluate the composed test battery exercises for knee injury prevention as functional based information.

Essential Points and Structure The master thesis contains several parts, starting with literature research on already existing methods and scores to measure and classify knee stability (Chapter 2). Furthermore, risk factors for an ACL rupture as well as exercises for knee stabilization and parameters describing the knee stability are of great importance (Chapter 3). Depending on several influence factors and already present prevention programs, a test battery was put together that consists of several parts: improve balance and proprioception, neuromuscular training for the optimization of inter- and intramuscular coordination and a strength training of the muscles around the knee (Chapter 4). Furthermore, the developed test set is intended to reduce muscular imbalances, analyze and self control one's knee stability in the context of a knee injury prevention program. This work shall contribute to increase awareness of injury risk and to provide exercises aimed to achieve an improved prevention. This prevention process includes different components, which are depicted in Figure 1.1 and the targeted interaction between them is depicted.

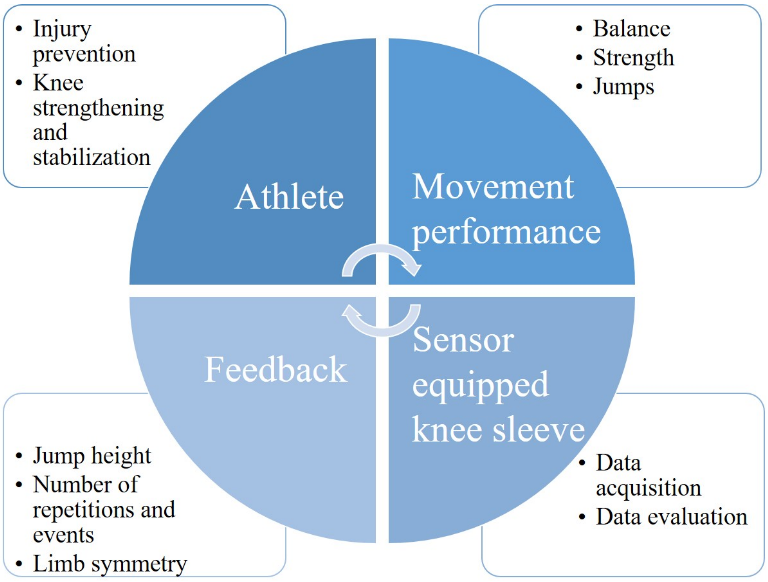


Figure 1.1: Targeted interaction between the different components for injury prevention and stabilization training. The movement performance consists of strength, balance and jump exercises and is evaluated by a sensor equipped knee sleeve which records the data and calculates exercise dependent parameters. These parameters are jump height and number of repetitions considering the limb symmetry and offer feedback to the user.

The aim of the master thesis is to develop a functional performance testing set which may objectively measure training progress and give feedback to the user. A key aspect lies on jumping performances and the evaluation of landing mechanisms. Therefore, the test battery includes several jump trainings to build and strengthen knee-protecting movements. The thesis focuses on the development of algorithms (Chapter 5) which filter and analyze raw sensor data, providing information that helps to calculate, evaluate and classify the performed tests. Therefore, a study for data acquisition was conducted to establish a link between the data of a sensor equipped knee sleeve and athletes' knee movement while doing the predefined exercises. According to the integrated sensors, the developed algorithms base on acceleration and angular velocity data and extract and evaluate knee stability parameters. For the data acquisition two of the previous mentioned sensor equipped knee sleeves including two IMU sensors are used. Based on the obtained parameters, the exercises and movement processes are evaluated while reference systems serve as basis to determine the accuracy of the algorithms. In conclusion the results are presented and discussed in Chapter 6. The last chapter of this thesis includes a summary of the procedures and results Chapter 7. It also provides a short outlook with recommendations for improvements and future research.

Chapter 2

Related Work

This chapter provides an overview of the literature research and related publications regarding knee functionality and existing injury prevention programs. Furthermore, the concept of the thesis as part of the project „Virtual Trainer“ (joint cooperation project of adidas® AG and Otto Bock HealthCare GmbH) is described.

2.1 Literature Review of Related Publications

2.1.1 Scores for Knee Functionality

There already exists a range of functional knee scores depending on questionnaires which are often part of a therapy program. More than 40 knee rating scales have been published since the mid 1980's, however few with proven reliability [BW99]. Two of these subjective scales are the modified „Cincinnati Knee Rating System“ and the „International Knee Documentation Committee Scale“ which combine a variety of symptoms with daily activity and objective physical findings. In the following, these scales are explained in detail and the „Melbourne Return to Sport Score“ will also be presented which is a criteria driven ACL rehabilitation protocol. As jumping tests are an important part in rehabilitation and prevention programs the Landing Error Scoring System is also presented.

Modified Cincinnati Rating System One of the most commonly used scores for knee injury is the Cincinnati Knee Rating System which is considered as gold standard in the development and validity [BW99]. It gives the therapist information as to how one's knee pain has affected his ability to manage in everyday life. Moreover, it consists of questions regarding pain intensity and swelling but also questions on daily and sporting activities.

International Knee Documentation Committee Scale (IKDC) The IKDC form is a patient reported outcome instrument consisting of 19 questions regarding symptoms, function and sporting activities. This score is calculated by predefined values for each question and widely used in clinical research and patient care for scoring knee joint diseases and injuries.

Melbourne Return to Sport Score (MRSS) The Melbourne Return to Sport Score is an assessment tool following ACL reconstruction for examining the end of the rehabilitation process [Gaj13]. It consists of clinical examination (stability, swelling, movement range), subjective knee evaluation and functional testing (e.g. balance, single hops, single leg squats). In total a score of 100 can be achieved whereby a score greater than 95 indicates a greater chance of returning to pre-injury sports.

Landing Error Scoring System (LESS) Padua et al. [Pad15] presented a scoring system with the focus of the short period of landing from a drop jump as a screening tool for an ACL injury prevention program. The drop jump is recorded in the sagittal and frontal plane on video and the landing movement is rated on the basis of a test protocol. For each performed task the user gets points to form a score. The higher the score the better the landing quality. A special significance lies on the knee performance, however, the whole body movement is analyzed. Exemplary the knee flexion angle has to be greater than 30° and the trunk should not be inclined to one side during the initial contact.

2.1.2 Exercises of Existing Prevention Programs

Among the mentioned questionnaires there are also several prevention programs with the aim of reducing the incidence of knee injuries in athletes considering the knee movement and ability in specific exercises. Donnel-Fink et al. [DF15] evaluated the effectiveness of several neuromuscular training programs for men and women to reduce knee or anterior cruciate ligament (ACL) injury. The most common program components are plyometric (jump training), balance exercises, strength training, running and stretching exercises. Further details and an exact list can be found in the appendix in Table A.1. Most prevention programs consist of a multidimensional approach, also referred to as test battery, which capture multiple motor skills. Gustavsson et al. [Gus06] developed such a test battery „to discriminate between the hop performance of the injured and the uninjured side in patients with an ACL injury.“ It consists of 5 tests: vertical jump, hop for distance, drop

jump followed by a double hop for distance square hop and side hop. Another test battery is presented by Noyes et al. [Noy91] which is a combination of two horizontal hop tests, single-leg hop for distance and a timed hop to increase the sensitivity.
Especially in football ACL ruptures are recurrent. A common test battery is the „11+“, which is a warm-up program for injury prevention, published by the German Football Association (DFB) and the FIFA Medical Assessment and Research Center (F-MARC) in order to minimize injury risk of football players. Significant numbers from 30-50% reduction of injury risk are presented in the publication. The program was developed from a group consisting of international experts and includes three different parts:

- running with active stretching and controlled body contact
- exercises to improve and strengthen the muscle activation (balance, strength, plyometrics)
- running, sprinting, jumping.

Each exercise is explained in detail (starting position, repetitions and what exactly needs to be respected) and pictures show the correct body posture and also executions that should be avoided [Biz07].

2.2 Thesis as Part of the Project „Virtual Trainer“

The project „Virtual Trainer“ regarding knee stabilization and injury prevention aim at people who need support or have a risk of knee (re-)injury. The sensor equipped sleeve provides assistance for private, location-independent training sessions to monitor selected exercises (e.g. strengthening muscles around the knee). The process is depicted in Figure 2.1 and describes the concept of „Virtual Trainer“.

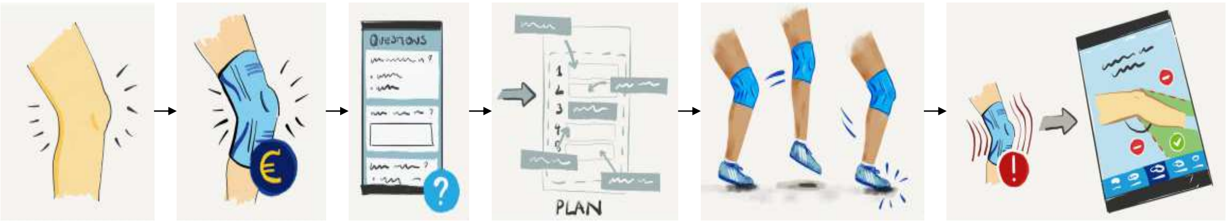


Figure 2.1: Concept and workflow of the virtual trainer project according to [Adi17].The user, suffering from knee problems, performs several exercises with the sensor equipped knee sleeve which calculates the FEA and provides feedback to the user.

The knee sleeve finds application for people feeling unconfident and insecure about their knee. After entering health related information they get a training plan to perform assessment tests. The users wearing the sleeve during the recommended training exercises gets automated feedback on their smartphone via Bluetooth Low Energy, whether the exercise was performed correctly depending on the knee flexion-extension angle (FEA). The user's progress to the next level is time-independent so it just depends on function-based milestones. Until now, the FEA can be measured using the knee sleeve and is used to count repetitions of several exercises. The algorithms for knee stabilizing parameters, which are developed in this thesis, serve as a further feedback method and to measure one's progress. They not just interpret several exercises but also consider jumps which are used for the assessment of functional stability and motor capacity (more precise description in Section 4.1) and analyze the knee movement in the frontal plane at landing.

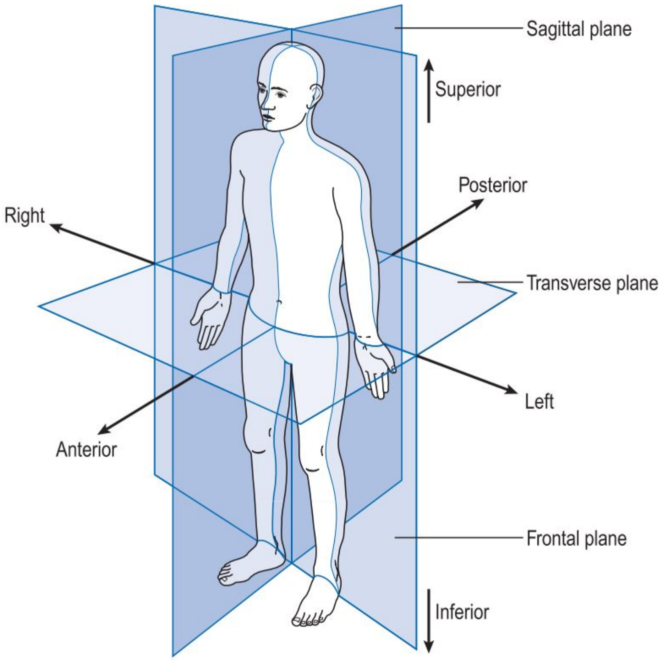
Chapter 3

Medical Fundamentals

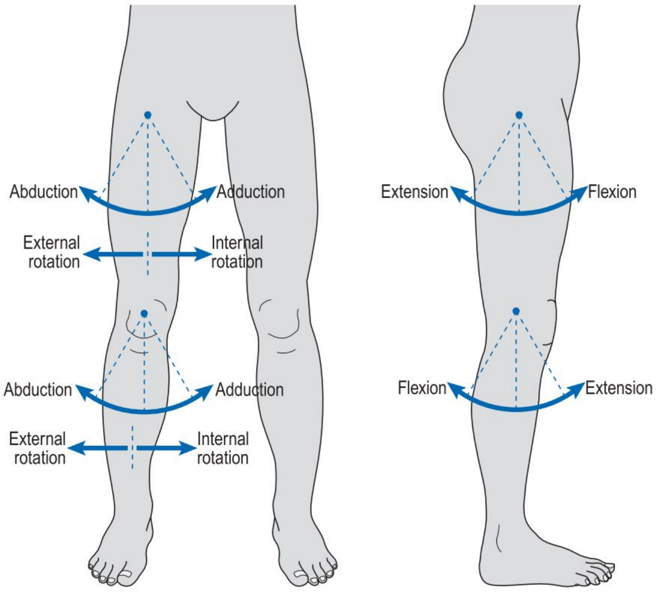
In order to understand the mechanisms leading to injuries, medical information about the human knee is provided in this chapter. The knee is the biggest joint in the human body with a movement capacity in two levels which are flexion and extension as well as external and internal rotation [Ses17]. In Figure 3.1 the anatomical terms for describing the anatomical positions and the relationship between different parts of the body are illustrated. The anatomical planes are useful when describing the motion of the limbs. In the case of knee movement the most important movements are flexion or extension, which take place in the sagittal plane, abduction or adduction in the frontal plane and internal or external rotation in the transverse plane. The varus or valgus alignment is also of great importance when analyzing knee stability and describes „an angulation of a joint towards or away from the midline, respectively“ [Whi06]. The range of motion is a three-digit code indicating the (knee) joint mobility. Thus, each movement and also each movement restriction can be clearly indicated. Mainly extension and flexion movements (from 120-140°) of the joint are significant. Furthermore, a rotation of 50-60° is possible [Smo16].

3.1 Anatomy of a Human Knee Joint

The human knee (lat. Articulatio genus, depicted in Figure 3.2) is a hinge joint consisting of thigh bone (femur), shank bone (tibia) and kneecap (patella) [Zac06]. Latter is a great sesamoid bone increasing efficiency of the quadriceps tendon and reduces joint strain. Between the condyles of thigh and shank lie the fiber cartilaginous plates (Meniscus medialis and Meniscus lateralis) [Zac06]. Their use consists in the enlargement of the contact surface between tibia and femur as well as the compensation of incongruences between the condyles.



(a) Body Planes



(b) Body Movements

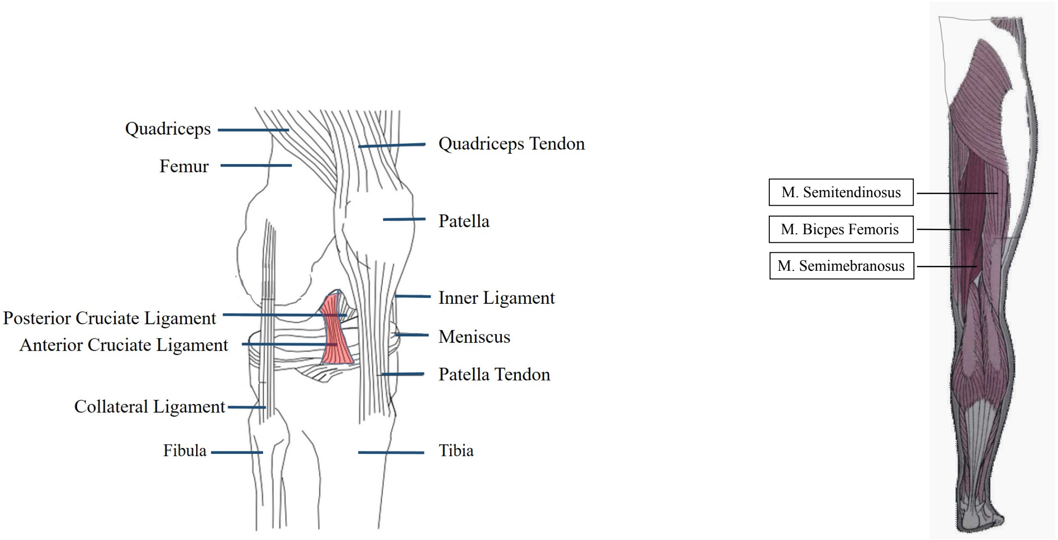
Figure 3.1: In (a) the three reference planes (transverse, sagittal and frontal plane) as well as the six fundamental directions are depicted. Figure (b) shows the movements of the lower limb [Whi06].

Sliding surfaces and especially ligaments are responsible for the knee stability. Interaction of bones, muscles, ligaments and tendons cause rotational, rolling and sliding movements, while the knee is mainly led ligamentally. The most important ligaments are the collateral ligaments (lateral and medial) and the cruciate ligaments (anterior and posterior). The collateral ligaments are responsible for the lateral guidance and stabilization of the joint especially when the knee is in a stretched position. They support the knee capsule, are tensed when the leg is stretched and thus strengthen the knee against lateral displacement and external rotation. If the knee is flexed, the ligaments largely go limp and thus allow rotational movements. With increasing flexion in the knee joint, the sidebands relax, allowing rotation of the lower leg. The cruciate ligaments running in the knee joint are intended to prevent the thigh from sliding back and forth on the lower leg. The two strong, crossing over bands limit the sagittal displacement and internal rotation of the joint parts. Table 3.1 offers a summary of structures responsible for knee stability and their impact. The passive stability of the knee joint is achieved by the medial and lateral sidebands as well as the anterior and posterior cruciate ligaments [Zac06].

Bursae in front of and below the knee protect the joint at the friction points of the tendons. Both muscles of the pelvis and the thigh area, as well as the M. popliteus stabilize the joint and support flexion and rotation. The menisci lie on the tibial plateau, increasing the contact surface of the incongruent femorotibial articular surfaces during movement and also stabilizing the knee joint.

Stability	**Structure**	**Impact**
passiv/ static	Outer Ligaments	apply axial forces; support again lateral give-way
	Cruciate Ligaments	absorb thrust
	Menisci	Reduction of pressure on the femoral and tibial articular surfaces; removal of voltage spikes; compensation of incongruities of the articular surfaces
active/ dynamic	Muscles	absorb shear force and thrust
	M. Quadriceps Femoris	prevents buckling of the knee joint
	M. Gastrocnemius	stabilizing knee joint during bounce phase

Table 3.1: Anatomical structures which are responsible for knee stability and their impact on the joint (according to [Ses17]).



(a) Simplified illustration of the human knee [Ses17]. The ACL is highlighted in red.

(b) Hamstring muscles on the back of the thigh [Geh12]

Figure 3.2: **(a)** Figure of the knee with for this work most important structures. **(b)** The hamstring muscles support the function of the cruciate ligaments and act as antagonist to the M. quadriceps femoris. Shortened hamstring muscles increase the risk of injuries and a balance between these muscle group and the ventral thigh muscles is important for the knee stability.

The musculature of thigh and shank is responsible for the knee movement. Muscles on the dorsal thigh are flexors for the knee joint and extensors in the hip joint (M. biceps femoris, semitendinosus, semimembranosus). They are connected between the ischial tuberosity and the thigh and form the so-called ischiocrural muscles. On the ventral thigh M. sartorius, M. rectus, M vasti (M. vastus medialis, intermedius, lateralis) associate with M. rectus femoris and M. quadriceps to one tendon enclosing the patella. The extensors develop three times more force than the flexors (meets the requirements of upright posture and gait) [Smo16]. Due to muscular imbalances of the thigh musculature the flexors are more injury-prone than the extensors. The reasons for this are greater power of the extensors (flexors' power is normally 2/3 of the extensors power) and the tonic state that leads to shortening and tension [Geh12]. Muscular imbalances can lead to ligament injuries and therefore exercises to strengthen the ischiocrural muscles are important.

Before a physical check-up there is an inspection of the knee regarding leg axis and lengths, musculature of thigh and shank in comparison, position of patella and malpositions. The flexibility of the knee joint is actively and passively tested in the side comparison

[Ses17, Zac06]. The function of the ACL can be tested manually with the passive anterior drawer sign, passive Lachmann-Test and active Pivot-Shift [Sch14, Aum07, Mak13, Zac06].

3.1.1 Anterior Cruciate Ligament

The anterior cruciate ligament (ACL) is a central feature for movement coordination and runs obliquely forwards and downwards from the inside of the outer thighbone, where it attaches to the bony promontory between the outer and inner tibial joint surfaces. It prevents and ensures the displacement of thigh and shank and also converts the rotation and shear forces into compression force. This constitutes a selective advantage as menisci and cartilage are able to absorb high compression forces but not shear forces. The ACL consists of three fiber bundles whose purpose is to stabilize the knee at each flexion angle. The posterior cruciate ligament (PCL) is stronger than the ACL. It arises from the inner surface of the inner articular cartilage of the thigh and pulls obliquely rearward laterally to the bony elevation of the shin joint surfaces and to the tibia trailing edge. A further important task of the cruciate ligaments is to limit the inward rotation of the shank [Geh12]. After an ACL rupture this mechanism can be limited and the patients cartilage also gets damaged and injured. Therefore, the ACL should be replaced protecting these structures. Besides the mechanical function of the ACL it also contains sensors controlling the posterior thigh musculature via a control circuit. This provides control over the tibial plateau and muscle protection for the knee joint [Spo17].

3.1.2 Relevance of the Knee Angle

Axes of the spine and extremities suggest orthopedic deformities and malfunctions in the locomotor system [Smo16]. Axis misalignment leads to increased force peaks (valgus > varus). Even small axial deviations can lead to a strong shift of the loads. The Mikulicz-Line is defined as vertical line between the center of the upper ankle joint, knee and hip joint (Figure 3.3). A physiologically normal femortibial angle is 174°, whereas angles in the coronal plane greater 180° lead to a genu varum while angles lower 171° define a genu valgum.

Great influence on the patellafemoral joint has the force produced by the quadriceps muscle. To evaluate knee function it is therefore essential to analyze the biomechanical features. The Q-angle is a parameter which describes the lateral force on the patella (shown in Figure 3.3).

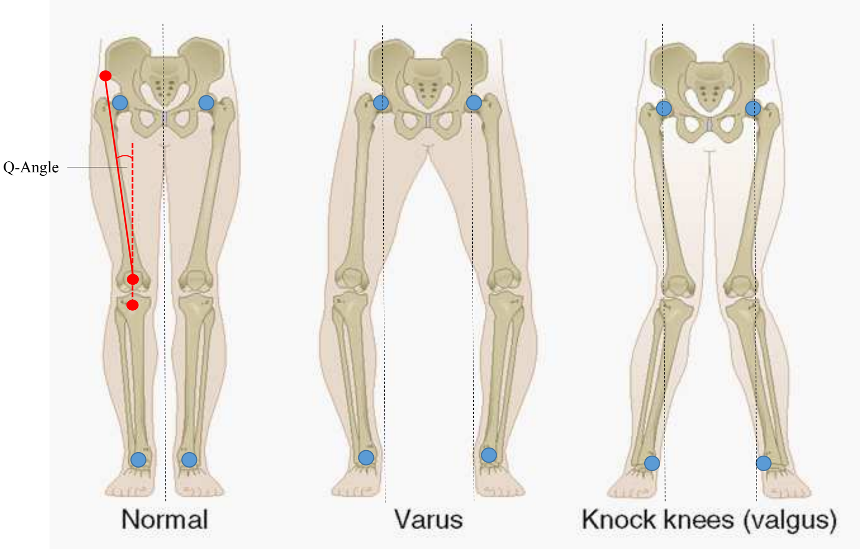


Figure 3.3: Defective positions of the human legs are defined using the so called Mikulicz-Line (dotted vertical lines) which is a line between hip joint and ankle joint. Angles in the coronal plane greater 180° lead to a *genu varum* while angles lower 171° define a *genu valgum*. Illustration according to [Goo16].

A normal Q-angle range is $13.5 \pm 4.5°$ (subjects between 18-35 years). However the Q-angle for women is 4.6° greater due to a wider pelvis and a relative knee valgus angle [Hor89]. The dynamic knee valgus is the change in the horizontal knee distance between the initial ground contact of a foot and the deepest flexion position during landing [Jöl11]. The occurrence of a dynamic valgus angle while performing jumps is a risk factor for ACL ruptures. As it is trainable, there is a chance to reduce this risk. Possible causes are fixed adductor muscles of the thigh and weak hip exterior rotators which can lead to an injury during landing after a jump, sudden stopping and rotary motions. In literature there are several methods to measure the knee angle when the patient is in a static position. However, measuring the dynamic medial and lateral knee angle presents a great challenge. In practice the recognition of problems with the motor control is done via optic-visual diagnosis. A special attention is turned to the knee movement in the frontal plane. A subjective perception could misjudge a medial knee movement as valgus angle. However, one has to consider that this movement is a combination of knee rotation and valgus angle.

3.1.3 Dynamic Knee Valgus

Considering the neuromuscular control (Section 4.1) the functional valgus is a high risk factor for ACL rupture and re-rupture [Hew13] and can be evaluated using several tests like single-leg-jumps, drop jumps ans single leg squats [Pet16b]. These exercises offer insights into landing stability and allow to identify athletes at risk for an injury. During jumps the dynamic knee valgus describes the change in the horizontal knee distance between the first ground contact of a foot and the deepest flexion position during landing [Jöl11, Pet16b]. Another method is to analyze the angle in the frontal plane. Therefore, a 2D camera system can be of assistance to analyze the position of the leg axis during landing which is the moment when the knee is most out of control [Pet16b]. A hazardous situation for an ACL rupture is a dynamic valgus >5 cm [Jöl11]. Single leg squats are a further exercise to analyze the dynamic knee valgus while care is taken to keep the knee above the foot center [Pet16b].

3.2 Risk Factors for an ACL Rupture

Injuries of the cruciate ligaments usually arise in torsion of the knee joint in flexion position, combined with a force acting on the lower leg from the inside or outside (varus or valgus stress). This often leads to tearing of the anterior or posterior cruciate ligament, often in conjunction with a meniscus or lateral ligament. These serious injuries result in a mandatory sport break for months and in some cases to the end of a professional's career. As protective measures a well trained thigh musculature is important as the ACL is functionally supported by the flexor muscles and the posterior cruciate ligament by the extensor muscles of the thigh. According to Bong [Bon14], common situations where ACL ruptures occur can be:

- a sudden change of direction (foot fixed in the floor, valgus movement, internal rotation, slight flexion of hips and knees)
- one-leg landing after jump (landing in valgus position, internal rotation, center of gravity behind the center of the knee joint)
- braking maneuvers (imbalances of knee extension and flexor muscles)

Injuries depend on interdependent factors. They could be induced by intrinsic factors (age, gender, anatomical factors, neuromuscular factors) or by extrinsic factors (sport equipment, environment) [May15]. Apart from these factors, good training equipment is essential and overtraining has to be avoided [May15]. The risk factors can be divided in trainable and not trainable ones (see Table 3.2). Not trainable risk factors are e.g. age and a sex-dependent different incidence rate. Depending on the sport, women have an increased incidence of ACL injuries than men in the same sport ([Rus06]). Among several factors this phenomenon is due to different landing mechanics and muscle activation and also hormones, which affect the metabolism and mechanical properties of the ACL [May15, Kia10, Rus06]. Malinzak et al. [Mal01] showed a difference of knee movement between men and women during several exercises. In single leg cross-cutting maneuvers the orientation of the knee for females has been shown to begin in valgus and moved towards further valgus. In comparison, male knee movement started in valgus and move toward varus alignment during the same task.

Not Trainable Risk Factors	**Trainable Risk Factors**
- Age: < 20 years - Sex: women - Hormone status: pre-ovulatory phase in women without contraception - Sport: soccer, handball, basketball, skiing - Pes pronatus valgus - Previous injuries of muscles and ligaments - Bad weather	- Dynamic valgus - Low hip and knee flexion during landing - Lack of hip and trunk control - Weak knee flexors and hip abductors (ratio to quadriceps) - Delayed recruitment of flexors - Proprioception deficits - Muscular fatigue - Bad general training condition

Table 3.2: Risk Factors for ACL injury divided in trainable and not trainable, according to [Pet16a].

Muscle fatigue is one of the trainable risk factors. Sport injuries often occur when a participant is fatigued at the end of a sporting event [Gus06]. According to Augustsson et al. [Aug04] hop performance under fatigued conditions has an improved sensitivity level. Furthermore, bilateral differences in lower limb features are important as they can increase the risk of injury and trigger compensatory mechanisms. This influences the motor performance. Possible causes of bilateral force differences may be inadequate rehabilitation or specific unilateral techno-motor demands due to the sport or training method [Haa12]. Another risk factor is the dynamic valgus as there is an increased risk for contactless ACL-ruptures due to knee-valgus-rotations and inner tibia (shinbone)-torsional moments (see Figure 3.4). Several studies showed that the dynamic valgus position is a risk factor for knee and also ACL injury [Pet16a]. Further risk factors are deficits in the neuromuscular control during dynamic movements and poorly trained proprioception in the knee joint. There are several exercises which help to improve and increase these deficits. Thus, not only muscles and bones, but also fascias, tendons, ligaments and cartilage. The risk for

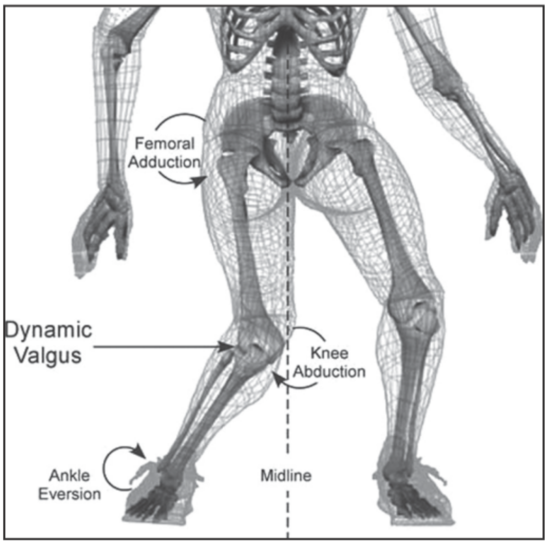


Figure 3.4: Typical movement of a dynamic lower extremity valgus which is a high risk factor for ACL rupture. The movement is a combination of rotations from the three lower extremity joints including femoral adduction, knee abduction and internal rotation [Hew10].

knee injuries appears not only to frontal-plane mechanism. A further factor is also a significant side-to side difference in lower extremity biomechanics and reduced relative lower extremity flexor activation. To evaluate the exercises for the prevention training, some knee injury prevention programs use the *Limb Symmetry Index*, hereinafter referred to as LSI. It is used or recommended in: [Blo17, Gok17, Gus06, Kel16b, Nes17, Pet17b]. Often, return-to-sport tests of strength and functional hopping rely on limb symmetry indices (LSI) to identify deficits. The LSI is the most frequently reported criterion of determining normal or abnormal hop test score and can be calculated with the formula:

$$\text{LSI} = \frac{\text{value}_{\text{affected}}}{\text{value}_{\text{not affected}}} \tag{3.1}$$

In this context „affected“ refers to the body side where the problems occur, as usually one side is more affected than the other one. The ratio should be greater than 85-90 %, otherwise there is a deficit. The LSI is the most frequently reported criterion for determining normal or abnormal hop test scores [Gus06]. Detecting functional limitations associated with ACL deficiency with the single leg hop test is relatively low [Gus06]. Therefore, a combination of several exercises will be used in the developed test battery. In some of these exercises the repetitions of events are counted to calculate the LSI.

Chapter 4

Parameters for Test Battery

During sports 72-95 % ACL ruptures arise in so-called non-contact-situations [Nes17] and occur predominantly without the direct action of the opponent. These situations could be landing after a jump, abrupt stopping and rotary motion [Nes17]. Mayr et al. [May15] name several general prevention principles of injuries. A key point is that injury prevention not only depends on proper equipment and training but also covers lifestyle and the mental condition. This includes proper psychological preparation as well as an appropriate diet to fulfill the functional requirements. Next to knowledge of correct training methods the recovery time plays a crucial role in prevention [Haa12]. A test battery was developed to train different muscles and to detect knee problems. Therefore, three requirements were taken into account:

- intra- and interindividual benchmarking
- individual strength and weakness profile
- training success control and training control/ updating.

The occurrence of a knee injury, ACL rupture in particular, is due to a combination of several factors. In this chapter, the developed stability program will be discussed considering the questions of which factors stabilize the knee joint and how to train and improve them. Therefore, a test battery was developed based on previous prevention programs to increase the stability through these exercises and gain risk minimization and injury prevention. Hereafter the development and components of the test battery is explained focusing on knee stability with the need to strike the balance between strength, endurance training, biomechanic aspects, balance and proprioceptors as depicted in Figure 4.1.

4.1 Components of the Test Battery

In this section, the components of the developed test battery for knee stability will be explained. These are strength training, balance and functional stability exercises. A battery of different kind of tests has been shown to be reliable and to have a greater ability of prevention, compared with any single test [Tho11]. A test battery is a combination of several single tests to gain a more valid test result. In this context, a heterogeneous test battery was developed including single tests with low intercorrelation to record complex skills. The aim is to identify physiological strengths and weaknesses and to evaluate the effectiveness of the training program of „Virtual Trainer“ (see Section 2.2).

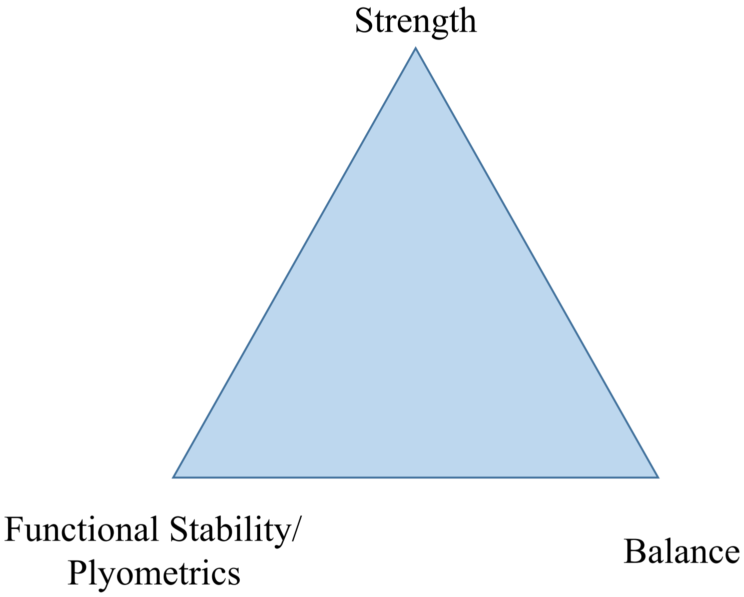


Figure 4.1: Essential components of the knee stability test battery for functional testing. The training set consists of three main parts: balance and proprioceptive exercises, strength and endurance tests and also exercises for functional stability including plyometrics and jumps.

4.1.1 Strength

The connection points between tendons and muscles respectively tendon and bone are particularly vulnerable. Joint stabilization can be achieved through the cruciate ligament and knee-joint surrounding muscles. A balanced musculature avoids one-sided strain. Further strength training is part of a protective function as the surrounding tissue is able to compensate great forces (e.g. during jumping). Also the trunk stability is quite important for providing dynamic stability. A lack of core strength and stability may predispose the athlete to injuries [Man13]. If muscle tension decreases due to fatigue, joint stability can also be reduced and the injury risk increases. Further risk factors are high imbalances between the strength of ischiocrural and quadriceps musculature and weak ischiocrural musculature which can lead to a clear overload of the anterior cruciate ligament with a potentially high risk of injury. Therefore, a strength training is necessary to prevent the athletes from injuries caused by strength deficits. Strength training causes a reduction in maximum tibial translation, protection of the anterior cruciate ligament and elevation of knee stability [Alt12] and therefore provides an increased joint stabilization as musculature is responsible for an even movement. Further advantages are strengthening of tendons, ligaments, fascia and joint structures leading to higher joint stabilization, improved posture, protective functions, repair of joint structures and more effective rehabilitation after injuries [Got13]. Definitely worth mentioning are the effects on the surrounding tissue structures due to strength training. The training reinforce the tendons, ligaments, fascia and joint structures. Increasing muscle mass increases bone strength and enhancement of all structures involved in the strength transmission process. A stronger bone leads to more collagen in tendons increasing the tensile strength. More collagen in menisci means increased elasticity of compression and shock resistance [Got13]. The strength of the ischiocrural muscles (also referred to as *hamstrings*, depicted in Figure 3.2) supports the function of the anterior cruciate ligament in a preventive and relieving way by preventing unphysiological translation of the lower leg from posterior to anterior parallel to the tibial plateau.

4.1.2 Neuromuscular Control and Balance

Neuromuscular control describes a complex interaction of different systems, which integrate several aspects: muscle activation and activity (static, dynamic, reactive), muscle coordination, stabilization, body tension, balance and anticipation skills. Neuromuscular training programs are also considered as effective prevention measurement for knee injuries [Biz07]. A decreased neuromuscular control can lead to a re-injury risk, as it is heavily influenced by abnormal trunk and lower extremity movement patterns. Especially excessive out-of-plane knee loads and particularly increased external knee abduction moments can raise the incidence for ACL ruptures [Hew05, Hew13]. Sensor motor exercises (e.g. single leg stand) help to train balance ability. The single leg stand can give orienting indications on muscle strength and coordination abilities [Smo16]. In this exercise the axis and the body's center of gravity is observed. In a proper execution all joints of the standing leg are in a perpendicular leg axis [Smo16]. The single leg stand is not only performed on a firm ground but also on a wobbling base. This places more stress on the neuromuscular system than normal hypertrophy training, as a destabilizing exercise environment provides a more variable and effective training stimulus. Thus, also improves the sensomotoric neuromuscular system.

Neuromuscular systems can be adapted also by strength training and are quite important to link motoric and sensory system. To train sensor motorization, neuromuscular systems and proprioceptors (balance/ body stability) have to be claimed. The exercises of this test battery are across systems, for example the strength tests also train stability and balance. Receptors in the knee regulate the forces on the ACL to prevent possible overloading. The so-called proprioceptors are also responsible for afferent information about the joint position [Pet16a] and are used for the neuromuscular control of a joint. Proprioceptive information comes from mechanoreceptors which can be found in muscles, tendons and skin. Furthermore, balance training can optimize the interaction between the different muscles.

4.1.3 Functional Stability and Plyometrics

The knee stabilizing muscles are a decisive factor to prevent ACL ruptures. Consequently, many cruciate ligament tears also occur at the end of a competition when neuromuscular fatigue has occurred. Regular exercises to promote neuromuscular coordination and proprioception have been shown to be effective in reducing the rate of cruciate ligament tears. Functional stability plays a very important part in this prevention program as it considers the knee stability during jumps and other dynamic exercises. There are complex coordinated requirements for jump exercises combining intra- and intermuscular movement coordination. Jump assessment is used as a decision-making tool since the 1990s to evaluate the dynamic resilience of patients [Kel16b]. There is also a test-battery which uses different kind of jumps to compare the affected with the non-affected leg. The Limb Symmetry Index (LSI) is used in these functional assessments to quantify side-symmetry [Kel16b]. „Vertical jump test can assess overall lower extremity power, bilaterally or unilaterally“ [Man13]. It is a measure of explosive anaerobic power. The executed jumps quickly activate contracting muscle fibers and challenge the autonomic nervous system, which promotes muscle strength and responsiveness. Since in a plyometric exercise the muscle is first stretched quickly and then strongly contracted, it is exposed to enormous strain. The word *Plyometric* is made up of the words plio *plythyein* (greek) = increase and metric = measure and is a method of developing explosive power, which is an important component of most athletic performance.

In addition, this type of training exercises means less stress to the body than strength or endurance training with the aim of sensomotoric control. This means optimization of reflex response and pre-activation of muscles. Plyometry is a combination of speed and power. It is understood as exercises characterized by fast-acting muscle contractions in response to rapid, dynamic loading or stretching of the involved muscles. In plyometric training, both the power of movement and the speed of movement are of great importance [Rad97]. Due to its exceptional variability and controllability, proprioceptive training is highly suitable for all performance and age groups as well as for the prevention and rehabilitation of injuries [Wei09]. When doing plyometric work, the muscle is stretched before it explosively contracts directly. The work in the strain-shortening cycle can achieve significantly higher load and force values than without. The plyometric training is intended to be the time between the yielding, eccentric muscle contraction and the beginning of the overcoming, concentric shorten contraction. By means of plyometric exercises certain movement patterns can be trained in a biomechanical correct way and the muscles, tendons and ligaments can be functionally strengthened. Plyometric training and agility exercises are important components of programs that have achieved good results, especially in the prevention of cruciate ligament injuries and other knee injuries [Biz07].

A lack in neuromuscular control (described in Section 4.1.2) can be a risk factor for ACL injuries which often occur without an external factor. In Table 4.1 the relationship between injury mechanism, neuromuscular imbalances and neuromuscular intervention is shown. The landing after a jump plays an important role as there are great forces on the ligaments and joints. Hewett et al. [Hew10] named four underlying neuromuscular imbalances: ligament, quadriceps, leg and trunk dominance, which can be the cause of injury mechanisms. To reduce the risk and to detect neuromuscular deficits jumping and hopping exercises are included in the test battery. Squat and drop jumps and also single leg hops for distance are part of the developed test battery. The squat jump is without countermovement and the take-off is a purely concentric muscle activation of the leg extensors. In the jumps, the power development of individual muscles with the corresponding frequency and recruitment of the motor units, temporal coordination between various joints and muscle actions of several different muscles, is combined. In the case of high dominance of the M. quadriceps and low ischiocrurale musculature there is an increased injury risk. Specific jump training can eliminate these muscular dysbalances (Cincinnati Sportsmetric Training Program). Performance in a vertical jump may be characterized by force or the flight height. The latter is the difference between height of the center of mass at the instant of take-off and at

Injury Mechanism Component	**Underlying Neuromuscular Imbalance**	**Targeted Neuromuscular Intervention Component**
Knee adduction during landing	Ligament dominance	Train for proper technique
Low flexion angle in landing	Quadriceps dominance	Strengthen posterior chain
Asymmetrical landings	Leg dominance	Train side/ side symmetry
Inability to control center of mass	Trunk dominance („core dysfunction“)	Core stability & perturb training

Table 4.1: Relationship between injury mechanism, neuromuscular imbalance and neuromuscular intervention for ACL injury prevention in female athletes [Hew10].

the peak of the jump [Lin01]. The vertical jump height is often used as a indirect technique to estimate power in the lower limbs [Dia11] and is defined as the difference between the initial height and the highest point reached [Dia11]. There are some studies using the flight time (FT) method to determine the jump height, measured by a contact mat (CTM) or a similar system [Dia11]. In this thesis the flight time will be determined by extracting take-off and landing based on 3D acceleration data.
To evaluate functional performance after an ACL injury commonly single leg hop tests are used. In general, hop tests has shown high specificity (94-97 %) but lower sensitivity (38-58 %). But the sensitivity can be improved to 62 % by combining different hop and jump tests [Noy91]. The sensitivity of the single leg hop test could also be improved up to 84 % when a one rep max strength test was considered [Aug04]. As there are no weights included in the test battery the users do single leg squats to fatigue before hopping.

4.2 Exercises for the Test Battery

There are already existing prevention programs containing different exercises as described above. In addition, a detailed overview is in the appendix in Table A.1. The test battery in this work, for increasing knee stability, contains a small selection focusing on fulfilling the requirements for the different components (see Section 4.1). The following exercises were chosen because of their preventive effect according to the previously discussed risk factors. They are used in several publications and are proven scientifically or based on experience. However, these exercises might not be sufficient as a return-to-sport program and also not for a full prevention and knee stabilizing training or workout. As the exercises were chosen with the precondition that they are measurable and evaluable with the sensor equipped knee sleeve the test battery may be a tool for detecting weakness in the knee in different load situations and for providing feedback to the user.

Some of the exercises strengthen the trunk and leg musculature and improve the static, dynamic and reactive neuromuscular control. They also train the balance and jumping technique. Important for all three components is the right technique. With special attention to correct posture and good body control, especially straight leg axis, knees bend so that they do not stick out over toes and gentle landings [Biz07]. The combination of jumps and strength training of the jumping muscles improves the jumping performance of all jumping forms significantly in comparison to only jump training and only strength training [Ada92, Wir11].

The order of the exercises results not only from the ascending degree of skill. It is started with the balance exercises and continued with strength and endurance tests. In the end jumping and hopping tests are performed. Sport injuries often occur when an athlete is fatigued, therefore the exercises are ordered respectively. To get an improved sensitivity level the tedious tasks are previous to the jumps and hops. Thus, the jump and hop performance were under fatigued conditions (also described in [Aug04]). The prescribed order of the exercises (Balance - Strength - Jumps) is also important to ensure a continuous warm-up before the jumping part starts. The aim of the test battery was not only to provide a test set as injury prevention but also to have the possibility to train at home or outside as it is simple and requires no further equipment (except the sleeve). It contains a warm up program with different levels of difficulty and efficiency as the exercises train different aspects. The test battery consists of two levels. In comparison to level I there are altered predefined requirements.

Leg dominance can be a risk factor for knee injuries. Therefore, single leg balance and single leg hopping techniques will be performed and are useful for addressing leg dominance. The complex human body can compensate weakness of one side while performing the exercises. In the second level of the test battery the focus is on single leg movement patterns to compare and detect imbalances. An other reason is that the more single leg activities an athlete performs, the more side to side symmetry is restored [Hew10]. The body uses neuromuscular feedback loops to influence symmetry during dynamic control of such tasks. Hewett et al. [Hew10] also declares that maximum cross-over effects are achieved when both lower extremities are utilized alternately in single limb activities. In the following, each exercise is explained with its benefits, performance and the parameters to be measured.

The order of the described exercises is the same in which they are performed. The exercises are intended to correct the dynamic valgus position and to strengthen the muscles of the posterior chain (knee flexors, hip abductors).

4.2.1 Single Leg Stand

The single leg stand, depicted in Figure 4.2, is the first exercise of the test battery and is recommended in [Biz07, Hew10, Pet17a]. Single limb balance and external perturbations (standing on blanket) are especially helpful in decreasing leg dominance [Hew10]. The single leg stand (also: unipedal stance test) is used to detect subtle balance impairments [Spr07]. In Level I the users stands on firm ground while in Level II the exercise is on a folded blanket. To shift the body's center of mass a ball is held in front of the user with outstretched arms.

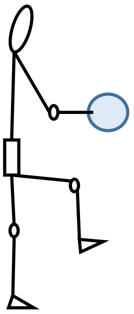


Figure 4.2: Single leg stand on firm (level I) or wobbling ground (level II) with open and closed eyes, alternating on right and left leg.

Benefits: This exercise improve strength, stability, proprioceptors, coordination of leg musculature and balance [Biz07].

Starting Position and Execution: The user is standing on one leg and holding a ball in front of the body for 60 seconds. The hip, knee and foot of the standing leg form a straight line. The other leg is angled forwards. It is necessary to ensure that the upper body is stable and the pelvis is in a horizontal alignment. The knee of the standing leg should not be bent in the coronal plane. The exercise is first done with eyes open (right leg, left leg afterwards) and with closed eyes subsequently (right and left leg).

Parameter: In Level I and II the single leg stand is performed with eyes open and closed, respectively on alternating legs and the LSI (3.1) is calculated using the standing times. The time was stopped to measure the amount of time the subject was able to stand on one leg. The time ended when the participant touched the ground with the other leg, was hopping or opened his eyes on eyes closed trials.

4.2.2 Glute Bridge

Strengthening the hamstring musculature is an important factor in the prevention program. A precondition of the program is the autonomous exercise of the tests. The glute bridge exercise Figure 4.3 can be done without a training partner and also no equipment is mandatory. In level I the glute bridges are performed with both legs parallel on the ground. Level II increases the training effect performing the exercise with just one foot flat on the ground. The single leg glute bridge is a more appropriate progression. The base of support is reduced and is effectively off center of mass. The athlete has to recruit the gluteus medius and minimus as well as the bracing muscles in the trunk to keep the pelvis level as the hip extends [Bre17]. Freckleton et al. [Fre14] found out that players who sustained a right hamstring muscle strain injury had a significantly lower single leg hamstring bridge score and were more likely to have a right knee injury.

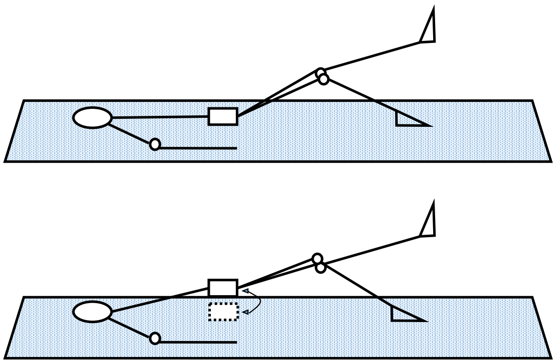


Figure 4.3: Glute bridge exercise (single leg) for strengthening the hamstring muscles. The foot is fixed on the ground while the hip is lifted and lowered repetitively.

Benefits: The benefits are training and strengthening of torso and hip muscles. While doing this exercise the glutes and hamstrings are trained as well as the hip extensor function of the gluteus maximus. The gluteus maximus, medius and minimus are important for hip flexibility and movement [Bre17]. Also the lower back is strengthened.

Starting Position and Execution: The user is lying face up on the floor with both feet flat on the ground and arms at side. The initial flexion-extension knee angle should be about 100°. Hip lifting off the ground to form a straight line of knee, hips and shoulders. Holding position for a second then easing back down slowly and repeat again. The higher the knee angle the more hamstring muscles activation. Level II: Starting exercise in same position, bending knees, raising one leg stretched out straight off the ground to form a straight line of knees, hips and shoulders as depicted in the picture above (Figure 4.3). Slowly lower the back, then repeat on the same side.

Parameter: The user performed the exercise while the repetitions were counted within one minute. In level II the number of repetitions of both legs were compared using the LSI (3.1).

4.2.3 Squats

Squats, especially single leg squats are highly recommended in literature and pre-existing prevention programs [Biz07, Cro11, Gaj13, Kel16a, Nes17, Kia10, Pet16a, Pet17a, Wil06]. One-legged squats are also screening tests to identify athletes at risk with a dynamic knee valgus [Pet16a]. In level I squats (Figure 4.4) and in level II single leg squats (Figure 4.5) are performed.

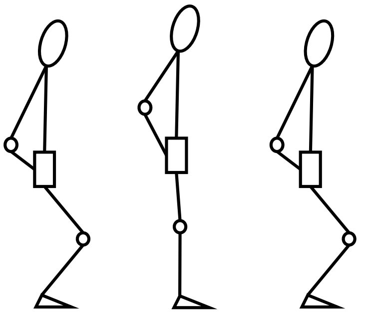


Figure 4.4: Squats

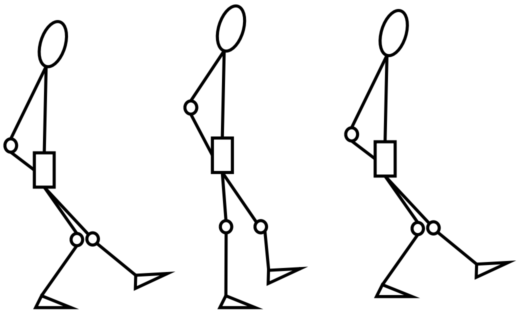


Figure 4.5: Single leg squats

Benefits: The development of lower extremity strength, endurance and the explosive power associated with sports [Nes17] are trained with this exercise. Beside core and hip muscle training, it also strengthens the thigh (M. Quadriceps, Hamstrings) and calf muscles, as well as M. Erector Spinae, M. Gluteus Maximus and training of movement control and knee joint stabilizing [Biz07].

Starting Position and Execution: The user is standing straight, placing feet shoulder-wide and arms crossed over breast or straight forward. He then slowly bends the knees parallel to about 90° and raise body up again. The knees should neither extend beyond the toes nor bend medially and the back should be inclined straight.

Parameter: In level I the exercise was performed for 60 seconds while the repetitions were count. In level 2 the number of repetitions of each leg were counted and compared using the LSI (3.1).

4.2.4 Drop Jump

The drop jump in Figure 4.6 is part of the plyometrics training exercises. A proper landing and take-off in a jump is quite important as well as soft and controlled landing. The height of the box has influence on the jumping performance. According to various studies, greater leaps in height are achieved in medium dropping heights than in low and large dropping heights [Art00]. The drop jump is part of several test batteries for injury detection and prevention: [Gus06, Hew13, Kel16b, Noy15, Pet17a, Pet16a]. The performance in the drop jump is determined by the high-speed capability in the short stretch-shortening cycle. The musculature works eccentric-concentric and a ground contact time (time between landing from box and take-off for vertical jump) below 200 ms is aimed. Performance-determining factors here are the maximum increase in strength, the elastic properties of the muscle-tendon system and the stretch reflex. The shorter the resting time on the ground, the better developed are reactive force and intramuscular coordination.

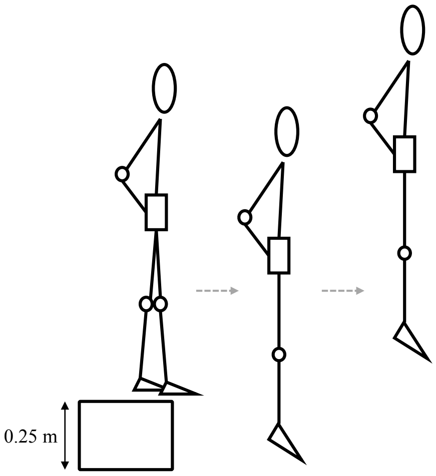


Figure 4.6: Drop jump performance from a 25 cm box.

Benefits: The drop jumps (Figure 4.6) increase and improve neuromuscular control to optimize inter- and intramuscular control. High out-of-plane loads and particularly increased external knee abduction moments [Hew13] take place in this exercise and can be a great indicator for knee instabilities. This exercise also evaluates the dynamic strength, trains movements control of the user and also identifies athletes at risk.

Starting Position and Execution: The drop jump is a vertical jump after landing from a drop height (25 cm). The user releases himself from the box by swinging his leg forward, initiating a brief phase of free fall (Instructions: „Jump as fast and as high as you can.“).

This is followed by a short support phase that begins with an eccentric contraction in the leg extensor muscle, slowing down the negative impact velocity to zero. In the subsequent concentric leg extension, the vertical take-off speed is generated after the shortest possible ground contact time to jump as high as possible. Landing should be flat on the footpads without heels on the ground and knee joints only slightly bent. Subsequently, a bouncing jump off as high and as short as possible will be performed.

Parameter: The contact time and the jump height are calculated, latter shows the quality of the intermuscular coordination. The quotient of jump height and ground contact time is called reactive strength index (RSI). It can be discussed as a form of speed strength and is the ability of the musculature to store energy in the elastic parts during the stretching phase during a so-called „stretch-shortening cycle“. The stored energy is then released as part of the muscular contraction, with the aim of increasing the development of force in this phase of movement.

4.2.5 Squat Jump

The squat jump is, as the name suggests, a vertical jump starting from a squatting position (FEA of 90°) without countermovement. In level II single leg squat jumps are performed. Squat jumps are mainly used to determine the maximum strength level of the extensor muscles. The force development is only by concentric force development of the leg extensor muscles. This exercise (normal squat jumps and single leg vertical jumps) is recommended in [Bar90, Biz07, Hew10, Noy15, Pet17a].

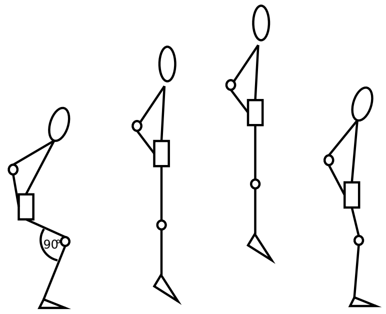


Figure 4.7: Sequence of actions in a squat jump (according to [Lin01]).

Benefits: The benefits of this exercise are training of jumping power and movement control [Biz07], individual performance and improvement control and detection of left-right asymmetries. Furthermore, squat jumps evaluate dynamic maximum power and leg and hip extension musculature and is a test of concentric stretching force.

Starting Position and Execution: The user is standing on both legs, feet are spaced out parallel to the width of the pelvis and hands are placed on the hips, as can be seen in Figure 4.7. Arm swing can effect the jump performance. To minimize these effects the participants were asked to keep the hands on their hips [Pic11] or crossed on the chest. They bent the knees to a right angle with inclination of the upper body. After a two seconds stay in this position the user performs a maximal vertical thrust, taking into careful consideration to land softly, not to bend the knees medially and not to land on the heels. Each participant performed a session of three trials. In level II the user performed three single leg squat jumps on the right leg and on the left leg afterwards.

Parameter: The jump height and also the knee movement in the frontal plane are calculated and evaluated.

4.2.6 Single Leg Hops

In literature there are several different one-legged hop exercises used in prevention and rehabilitation programs (see [Man13, Gaj13, Kel16b, Noy15, Noy91, Gus06, Kel16a, Tho11]). In this test battery single leg hops for 10 m are performed, depicted in Figure 4.8. An orientation strip of 10 m is placed perpendicular to a starting line. In level I the users make consecutive hops on one leg straight on. In level II the user hops for 10 m crossing over the center line each time (Figure 4.9). The landing must be controlled and the participant is not allowed to pause while hopping.

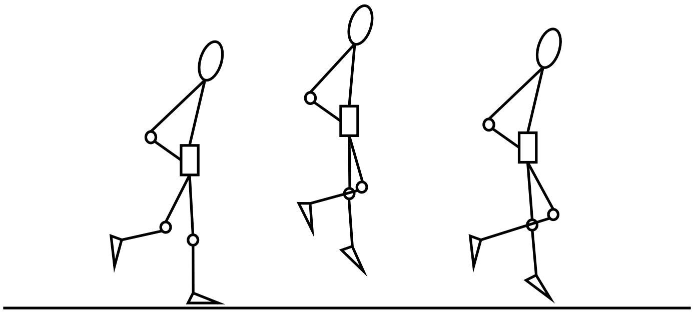


Figure 4.8: Single leg hops for 10 m.

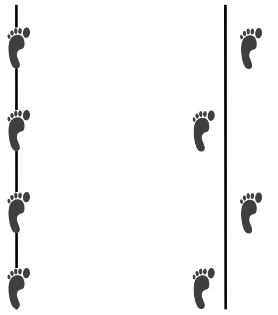


Figure 4.9: Single leg hops.
left: Level 1
right: Level 2

Benefits: The single leg hops improve the strength of the knee extensors and the entire body musculature and also stabilize the joints. The one-legged motion design exposes the hip, leg and lumbar muscles to overloading. The exercise also stresses the muscles that stabilize the knee and ankle joints [Rad97].

Starting Position and Execution: Standing on the right leg for two seconds with a following hopping sequence for 10 m. At the end of the predefined way the user has to hold his one-legged position for approximately two seconds again. Free leg and arm swing was allowed. The subjects were instructed to perform a balanced and controlled landing and to keep the landing foot in place for about 2-3 s. After a one-minute break, the same exercise was repeated with the left leg.

Parameter: The number of hops was counted for each leg and compared with each other and also with the number of hops from the crossover part.

Chapter 5

Methods

In this chapter the movement analysis, which can be described as examination of sport technique to correct and optimize, and also the used hard- and software for the data acquisition will be presented. On the one hand there is a qualitative analysis which examines systematically the movement quality. On the other hand is the quantitative analysis that measures biomechanical parameters using electronic and optical measurements. At the beginning, the sensor equipped knee sleeve and the data logging process are presented in Section 5.1 to get an insight in the data acquisition procedure. A study has been conducted with male and female subjects who performed the exercises, described in Section 4.2 to receive data from several subjects. With these datasets the knee sleeve is evaluated. During the study the exercises were also recorded with reference systems (motion capturing system, force plate, video recording), which are explained in Section 5.2. Subsequently the data acquisition and exercise assessment are described in Section 5.3, and in Section 5.4 the event-based synchronization is explained. Following, Section 5.5, explains the different algorithms to extract and calculate the demanded parameters in detail. To identify unstable test subjects the jump exercises were labeled by biomechanical experts and the results were compared to the measured data in Sections 5.6 and 5.7. In conclusion, the accuracy of the algorithms are determined by comparing the results with the reference systems. The methods for evaluation and statistical analysis of the results are given in Section 5.8.

5.1 Sensor Equipped Sleeve

The sensor equipped sleeves are depicted in Figure 5.1, one for each leg with the left one back-to-front. The electrical system consists of a microcontroller Arduino$^{\mathrm{TM}}$MKR ZERO, two wired inertial measurement units, hereinafter called IMUs, and a vibration alarm. There are two pockets integrated for the IMU sensors to be fixed in a good position with less wobbling. The positions of the sensors were determined in [Mau17]. A third pocket extends the system and contains the vibration alarm. Depending on the performing exercise there are different thresholds for the FEA. If the threshold angle prior set is exceeded, the user will get a physical feedback from the vibration alarm.

Figure 5.1: The two sensor equipped sleeves which were used for the data acquisition. Holes have been cut in the sleeves to mark the positions, where the passive markers of the motion capturing system are placed.

For the measures two IMU sensors (BNO055, BOSCH Sensortec) including 3D accelerometer, 3D gyroscope and a 3D magnetometer were integrated in the sleeve (further details see [Mau17]). Sensor I is situated on the upper half of the sleeve on the front of the thigh. Sensor II is placed on the sleeves' lower part at the back of the shank. IMUs are based on micro-electromechanical systems (MEMS) and allow continuous recording of movement-related information [BOSa].

5.1.1 IMU Sensors

9D-Inertial measurement units are sensors which consists of three parts: triaxial accelerometer, triaxial gyroscope and triaxial magnetometer. In the knee sleeve two sensors BNO055 are integrated which are 9-axis orientation sensors, including sensors and sensor fusion in one package [Bosb]. Hereinafter each component is described. Although the magnetometer is not used in the data acquisition process, it is briefly explained for the sake of completeness.

Accelerometer

The first described component is the 14-bit tri-axial accelerometer with a range of $\pm 4\,\mathrm{g}$ [Bosb]. Acceleration sensors measure linear static or temporal movements over the occurring inertial forces. The measured acceleration $\boldsymbol{a}$ can be integrated to receive the velocity and a further integration provide the distance traveled in the direction of the measuring axis of the sensor. The structure of a classic accelerometer exists usually of a moveable mounted mass and an adjacent piezoelectric element. By accelerating in one direction, a force is applied to the piezoelectric element, producing a measurable voltage. Integrating three acceleration sensors, which are pairwise orthogonal to each other provides acceleration on each spatial axis of 3D space which detects linear motion and gravitational forces. The advantages of accelerometer in MEMS are a small size and weight and also low power consumption. However, they are not as accurate as accelerometers of traditional techniques [Woo07].

Gyroscope

The BNO055 contains a triaxial 16-bit gyroscope with a range of $\pm$ 1000°/s which measures the rate of rotation in space (roll, pitch, yaw) [BOSa]. A gyroscope is a rotation rate sensor giving the angular velocity $\boldsymbol{\omega}$ or yaw rate in degrees per second [°/s]. In many applications, the rate of rotation is not the actual measurable variable but the current direction and orientation of the body determined by the temporal integration [Fül12]. Gyroscopes, which are manufactured as Micro Electro Mechanical System (MEMS) usually consist of very small mass elements that are vibrated in one axis and whose movement is measured by the influence of the Coriolis force on capacitive elements arranged in a horizontal axis [Woo07].

Magnetometer

The third component is a triaxial geomagnetic sensor which measures the magnetic field strength in a given direction [BOSa]. It is prone to the magnetic disturbance in the surrounding environment such as strong electric currents. They can be fused with gyroscope data to improve the accuracy of the calculated orientation [Woo07].

5.1.2 Control of the Data Logging System

This section describes the components of the system which consists of several parts, depicted in Figure 5.2. The first part is the designed knee sleeve including the IMU sensors connected to a microcontroller. Raw data can either be saved on a micro-SD card or be analyzed on the microcontroller and sent to a smartphone via Bluetooth low energy (BLE). For recording the exercises a smartphone and a tablet (one for each sensor equipped sleeve) were used as remote control to log the data on the respective SD-card. After the test session the data was saved on a computer and analyzed with MATLAB® (The MathWorks,Inc., Version R2016b, Massachusetts,USA). Therefore, several algorithms were developed and explained (see Section 5.5) which extract the exercise dependent parameters to evaluate the performed exercises.

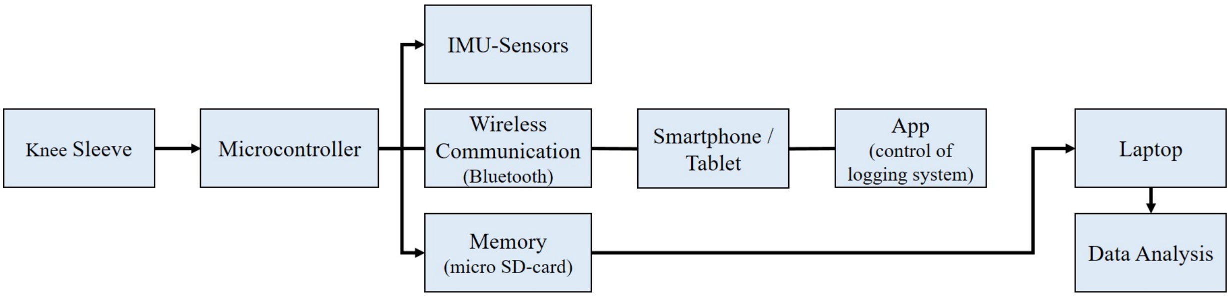


Figure 5.2: Block Diagram of the Data Acquisition System. The sensors from the knee sleeves are connected to a microcontroller which can be controlled by a smartphone via Bluetooth Low Energy. The recorded data is saved on a SD-card and can be analyzed afterwards.

5.2 Reference Systems

The participants of the data acquisition were equipped with two knee sleeves, including two IMU sensors on each sleeve. Apart from the sleeve sensors the movements were captured by 31 passive markers of a motion capturing system (Vicon Motion Systems Ltd UK, Oxford), placed on their lower body (hip, legs and feet) to obtain further information, e.g. knee angles. In addition to this reference system a force plate (Kistler Instrumente AG, Winterthur, Switzerland) was used to analyze the jump exercises. Each exercise was recorded on video, either with a camera (GoPro®, Inc., California, USA) or the motion capturing system.

5.2.1 Motion Capturing

For evaluating the knee angles a Vicon motion system [Pea05] was used. This is a tracking system and tool for movement analysis, containing 16 infrared cameras. Additionally two normal cameras are synchronized with the system. Reflective markers were positioned on bony anatomical landmarks (depicted in Figure 5.3),including hip, legs and feet, on the participant. Therefore, holes were cut in the sleeve. These passive markers are highly reflective and appear brighter than their surroundings. In addition, a ring of stroboscopic LEDs mounted around the camera lens housing is used to illuminate the tracking targets [Man04]. The markers were mounted directly on the skin, for each limb three markers to determine its position in 3D-space. The marker positions define the position and orientation of the limb segment. From these locations the position of the joint center is calculated via triangulation to a 3D model from which the required angles can be computed. Therefore, the Nexus software (Vicon Motion Systems Ltd UK, Oxford [Vic17]) was used.

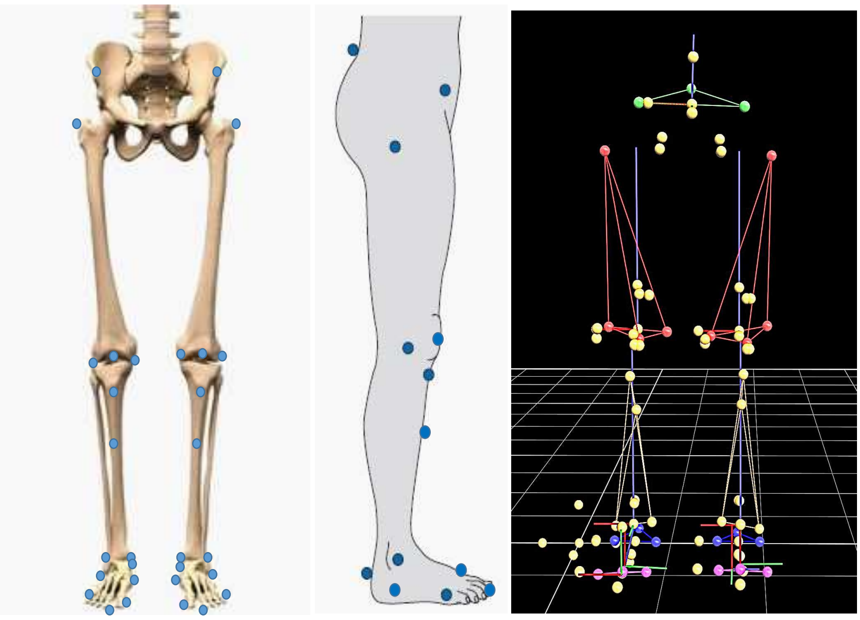


Figure 5.3: Positions of passive markers on anatomical landmarks (modified [Whi06]) from the Vicon system.

Marker-based motion capture is a frequently used motion capture method in biomechanical and clinical studies but has also deficits that limit the method's effectiveness. Errors can be introduced because of marker movement on soft tissue, like wobbling muscles, body mass and skin movement. This movement causes inaccuracies because the motion of soft tissue is different than the movement of bones, which are the structures of interest in biomechanical studies. A further source of error are markers which are not placed exactly on the right position and marker occlusion which occurs when a maker is unable to be seen by at least two cameras. These sources of inaccuracy should be kept in mind when evaluating the collected data.

5.2.2 Force Plate

Force plates measure the ground reaction forces and offer information about the moments, position and direction of the forces using piezoelectric measurement. They help to describe the interaction between a body mass and its force in three-dimensional space. Therefore, they are a often used tool for gait analysis and also for measuring jump height [Moi08, Dia11, Elv07]. A force plate (Kistler Instrumente AG, Winterthur, Switzerland) attached to the Vicon System was used to gain information regarding the jump exercises. Force plates are accurate for detecting jumps particularly at the times of take-off respectively landing. They can be obtained from the instantaneous vertical acceleration of the center of mass [Pic11]. The detected points can be used to calculate the jump height h with the time of flight T using the formula (5.14). The points in time of take-off and landing were extracted when the ground reaction force was 0 N as it has been set to zero previously.

5.3 Data Acquisition and Exercise Assessment

The present study was conducted with 17 healthy male and female participants with the average age of 25.6 ± 2.4 years. A more detailed line-up of the anthropometric data can be found in table Table 5.1. The data of one subject has been excluded because of hardware problems in the beginning of the study. In five other subjects, there were problems with the logging of the sensor data in isolated exercises. These exercises were left outside in the statistical evaluation. Each participant performed the exercises (described in Section 4.2 and in Table 5.2) with 60-second intervals between the trials. Between level I and level II was a 15 minute break. In Table 5.2 also the used reference systems and the requirements for each trial are listed. Each exercise is also recorded on a camera placed frontal to the subject. The jump exercises were additional recorded by a second camera perpendicular to the sagittal plane of the subject. The force values were recorded via the force plate. In addition, the movement was marked by important points on the subjects' bodies by means of markers of the motion capturing system Section 5.2.1.

Data	
Number of subjects	16
Number of male subjects	7
Number of female subjects	9
Body height (mean ± std)	176.4 ± 7.44 cm
Handedness right	15
Handedness left	1
Mean age (years)	25.6 ± 2.44

Table 5.1: Data related to the test subjects

In the beginning of the study each subject was asked to fill in two questionnaires regarding personal data and questions about their physical activity readiness and health. The first one was about their general health and the second one especially about current knee problems or injuries in the past. There was also a questionnaire after they finished the physical exercises, where the users answered exercise related questions whether they felt any pain or had difficulties in executing the exercises. The questionnaires are attached in Appendix D. After the participants gave their written consent they were equipped with two knee sleeves, for each leg. Then the passive markers were fixed on the anatomical landmarks (depicted in Figure 5.3) on their lower extremity and hip. They performed the exercises (as already described in Section 4.2) as follows. First the calibration process of the Vicon system has been done which is a static recording saving the individual anatomical marker positions. After recording the calibration movements for the functional alignment (Section 5.5.1) the exercises were performed. The sensor data (tri-axial acceleration and tri-axial angular velocity) for each trial was saved on the SD-cards connected to the microcontroller. For data logging a tablet and a smartphone (one for each sleeve) were used as remote control. However, the motion capturing system was just used for the squats, drop and squat jumps and the single leg hops of each level. The single leg stands and glute bridges were only recorded by the IMU sensors and a camera. For the trials with the motion capturing and force plate systems the participants stepped on the force plate before performing the jumps. The force plate is connected simultaneously with the Vicon system using the Nexus software. The sampling frequency was set 200 Hz (force plate and Vicon). The stamp on the ground can be recognized and the two datasets can be synchronized by peak detection of acceleration and force data respectively (Section 5.4).

Exercise	**Vicon, Force Plate**	**Video Data**	**Requests**	**Measured Parameter**
Level 1				
Static Calibration Vicon	✓			
Calibration Sleeve			5 s	
Calibration Sleeve			4 times	
Single Leg Stand, eyes open, right leg		✓	60 s	time
Single Leg Stand, eyes open, left leg		✓	60 s	time
Single Leg Stand, eyes closed, right leg		✓	60 s	time
Single Leg Stand, eyes closed, left leg		✓	60 s	time
Glute Bridge		✓	1 min	repetitions
Squats	✓		1 min	repetitions
Drop Jump	✓		3 times	height
Squat Jump	✓		3 times	height
Single Leg Hops, right leg	✓		10 m	LSI
Single Leg Hops, left leg	✓		10 m	
Level 2				
SLS, blanket, eyes open, right leg		✓	60 s	time
SLS, blanket, eyes open, left leg		✓	60 s	time
SLS, blanket, eyes closed, right leg		✓	60 s	time
SLS, blanket, eyes closed, left leg		✓	60 s	time
Glute Bridge, right leg		✓	to fatigue	LSI
Glute Bridge, left leg		✓	to fatigue	
Squats, right leg	✓		to fatigue	LSI
Squats, left leg	✓		to fatigue	
Squat Jump, right leg	✓		3 times	height
Squat Jump, left leg	✓		3 times	height
Single Leg Hops, crossover, right leg	✓		10 m	LSI
Single Leg Hops, crossover, left leg	✓		10 m	

Table 5.2: Order of the exercises divided into two levels. Between each exercise is a break of about one minute and between both levels a time to rest of 15 minutes. Each exercise is recorded with the IMU sensors. Additionally, depending on the exercise reference data was recorded using the Vicon system, force plate and video camera. This table shows the reference systems and also the requested and measured parameters for each exercise.

5.4 Data Synchronization

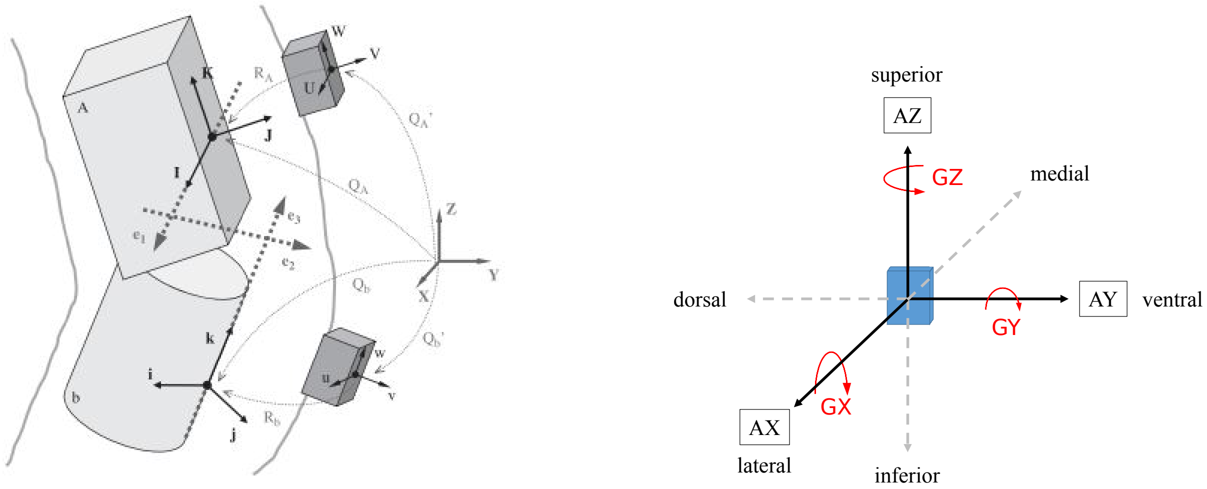
The Vicon System (sampled with 200 Hz) and the Force Plate (sampled with 200 Hz) are connected via wired synchronization. The sensors of the knee sleeve record data with 100 Hz. To synchronize the data of the sensors with the force plate and Vicon system, the participant stamped on the force plate once before each exercise. This movement was highly visible in the sensor and force plate data. Detecting these maxima in acceleration data from the sleeves' sensors and the force data from the plate the signals could be synchronized by detecting the extreme values.

5.5 Algorithms for the Analysis of Exercises

The recognition and evaluation of functional movement patterns of the performed exercises from the test battery is the key issue in this work. This is realized by using different algorithms which are applied to the sensor data from the knee sleeve. Depending on the exercise acceleration or angular velocity is more significant. In this section the detailed workflow and underlying methods for the developed algorithms analyzing the exercises are explained. Algorithms for the sensor alignment and the different exercises were implemented with MATLAB®. First, the functional alignment of the sensor position to rotate the raw data in a global coordination system is explained in Section 5.5.1. It is realized by performing two alignment movements [Mau17] and calculate a rotation matrix by using the principal component analysis (PCA). Following this, in Section 5.5.2, a method is introduced to extract the individual jumps out of acceleration data with the use of subsequence dynamic time warping (SDTW). This approach enables not only to detect several jumps but also to define the points in time of take-off and landing. Having these two timestamps the jump height can be calculated with the flight-time-method which is presented in Section 5.5.3. Subsequently, the algorithms for the individual exercises are explained in detail in Section 5.5.4.

5.5.1 Functional Alignment

The two IMU sensors are fixed in small pockets in the knee sleeve. Nevertheless, movement of the sensors is possible, as the sleeve is made out of stretched material and the manual position of the sleeve leads to a different position and orientation of the sensors. To reduce these sensor rotations, there is a sensor alignment with respect to a fixed absolute coordinate system which can be seen in Figure 5.4(a). A further reason to calculate a sensor alignment in the beginning of the evaluation was the different leg shape of the subjects and therefore various sensor positions and orientations. The anatomical calibration is using a functional approach by considering defined movements and calculation of a rotation matrix with gravitation and angular velocity data.



(a) Functional alignment [Fav09]. The two IMU sensors are placed on thigh and shank and applying the functional alignment they are rotated into a global coordinate system.

(b) Directions of the sensor axes in the global coordination system with the anatomical designations and directions.

Figure 5.4: Global coordination system classified in the anatomical position with sensor axes definitions (AX,AY,AZ form three accelerometer dimensions and GX,GY,GZ form the three gyroscope dimensions.)

To calculate the rotation matrices, the principal component analysis (PCA) was used which is a method of linear transformation of variables such that as few as possible new variables describe the relevant information and the new variables are orthogonal. The purpose is to build a model with the transformed data eliminating irrelevant information like noise. Using this method the data from sensors fixed in the sleeve can be rotated in the global coordination system to make them independent of their moving position.

Before performing the exercises each participant of the study did two calibration „movements“ [Mau17]. With these two datasets it was possible to calculate a rotation matrix which rotates the captured data from the sensor coordinate system into a global coordinate system. The first calibration was standing still for about 5 seconds and the second one was a lateral adduction-abduction movement of the leg in the frontal plane. This calibration process has been done for each sleeve (right and left leg). With the first calibration movement the vertical alignment can be realized. The acceleration data, consisting of vectors (comprising

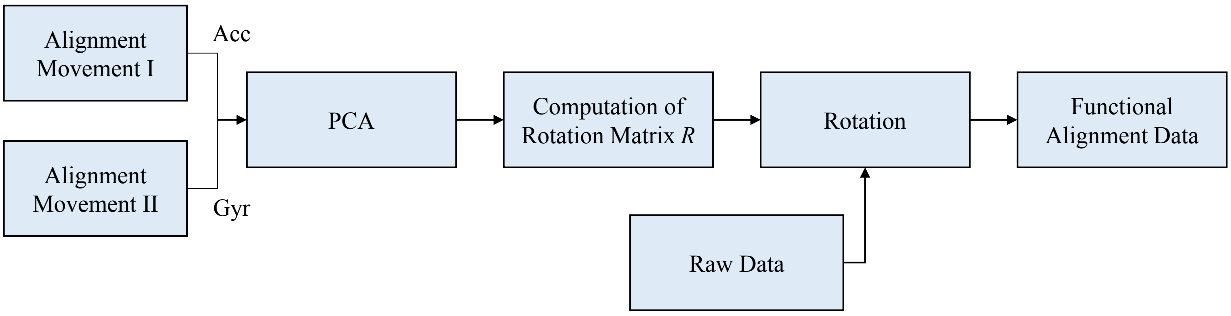


Figure 5.5: Workflow of the Alignment Process. The raw sensor data is rotated by a rotation matrix which is calculated using two alignment movements. As a result the acceleration and gyroscope data is in the global coordinate system.

gravity data for each direction) and representing the sensor orientation relative to the global z-axis were compared to the unit vector of $\boldsymbol{z} = (0\ 0\ 1)^T$. The second calibration movement was used for horizontal alignment to define the rotation to the global x-axis: $\boldsymbol{x} = (1\ 0\ 0)^T$. For the second calibration a lateral leg adduction-abduction movement was performed with attention not to move the leg ventrally. The recorded triaxial angular velocity data from the gyroscope was analyzed using the principal component analysis (PCA) to obtain a rotation matrix which rotates the raw data oriented in the local coordinate system into a global coordinate system (Figure 5.4(b)).

The rotation matrices are calculated using the two defined axis and an already existing algorithm from Wahba [Wah65, Mar88] which is described briefly. Before applying the PCA method the acceleration data is normalized and the mean of the angular velocity is calculated and then removed from every axis of the gyroscope data. Subsequently the covariance matrix of the altered angular velocity is computed. The covariance matrix C is a quadratic matrix containing the variances and covariances for several variables. The diagonal elements of the matrix contain the variances of the variables, the non-diagonal elements contain the covariances between all possible pairs of variables. Afterwards the eigenvalues λ and eigenvectors $\boldsymbol{x}$ are computed, so that $C\boldsymbol{x} = \lambda\boldsymbol{x}$. The eigenvector containing the maximal eigenvalue was used as movement vector. With utilization of singular value decomposition the rotation matrix was calculated. This procedure has to be done for each subject for the left and right leg respectively and the raw data of each exercise is rotated by these matrices. Figure 5.5 gives a summary of the alignment process. After rotating the raw data into a global coordinate system the algorithms for the exercises were devolved and applied to the data.

5.5.2 Subsequence Dynamic Time Warping

In the following, a signal processing approach for event detection is presented. Dynamic time warping (DTW) is an alignment technique to find an optimal alignment between two given patterns [Rab93, Mül07]. The advantage compared to template-based cross-correlation methods is that the template length must not have a fixed length and form so that some parts of the template get stretched or shortened (warped) non-linear for an optimal fit. This method is often used for stride segmentation [Bar15].

The objective of DTW is to compare two (time-dependent) sequences $X := (x_1, x_2, \ldots, x_N)$ of length $N \in \mathbb{N}$ and $Y := (y_1, y_2, \ldots, y_M)$ of length $M \in \mathbb{N}$ [Mül07]. As DTW compares two signals in complete it can not be used to detect several repetitive signal patterns. In this thesis there is not only a comparison of a test sequence with predefined references. The complete measurement dataset is scanned by a predefined template of one test person. The aim is to identify single jumps or repetitions from a signal. This can be realized with a special form of DTW called subsequence dynamic time warping (SDTW). The variability of different time lengths and signal amplitudes are taken into consideration with this approach. SDTW detects several occurrences of a test sequence in a longer data sequence. Figure 5.6 shows an example for DTW and also for SDTW.

The feature vector sequence to be recognized is compared consecutively with the complete stored pattern using SDTW. In this case so-called distance measures are used for the quantitative comparison of two feature vectors which can be calculated by any p-norm [Bar15]. In this work the Euclidean norm is used.
Given two signal sequences, test template T with $T = (t_1, \ldots, t_M)$ of length $M \in \mathbb{N}$ and sensor data S with $S = (s_1, \ldots, s_N)$ of length $N \in \mathbb{N}$ a distance matrix D based on the euclidean norm can be calculated:

$$\mathbf{D}(m,n) = \sqrt{(y_m - x_n)^2}, \forall m \in \{1, \ldots, M\}, n \in \{1, \ldots, N\} \tag{5.1}$$

Each row represents the distance between one sample of the template T and the sequence S. Typically the local distance d is small (low cost) if samples t_m and s_n are similar, and otherwise d is larger (high cost). The aim is to find an alignment between T and S having minimal overall cost. Müller [Mül07] defines this so-called warping path as a sequence $p = (p_1, \ldots, p_L)$ with $p_l = (n_l, m_l) \in [1:N] \times [1:M]$ for $l \in [1:L]$ satisfying the following three conditions:

(i) Boundary condition: $p_1 = (1,1)$ and $p_L = (M,N)$

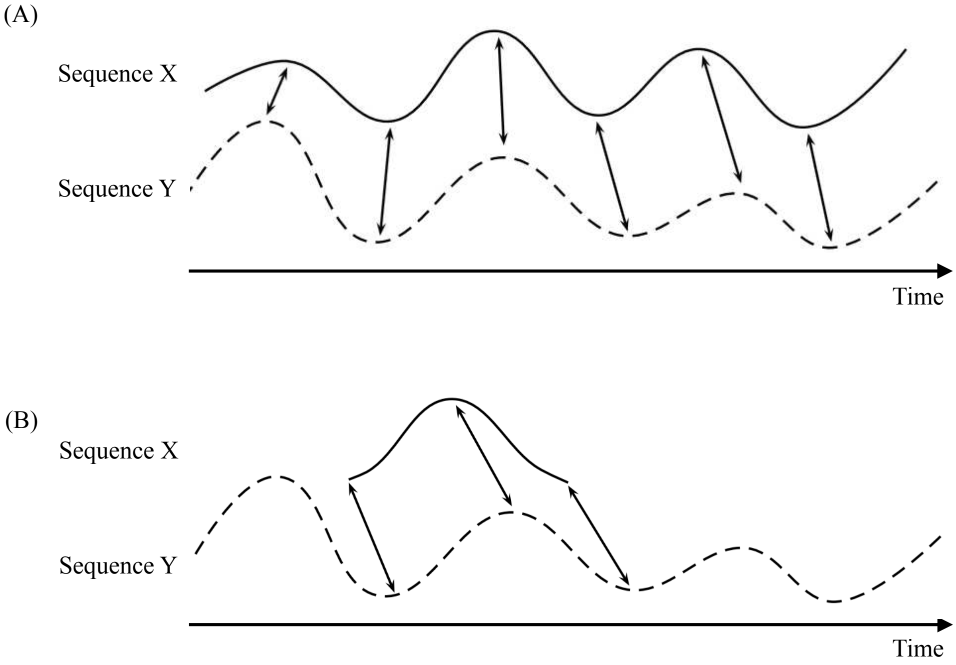


Figure 5.6: DTW for comparison of two signals. (A) Time-alignment of two sequences of different lengths. The arrows indicate the aligned points. (B) Subsequence dynamic time warping with a subsequence of Y [Mül07].

(ii) Monotonicity condition: $n_1 \leq n_2 \leq \ldots \leq n_L$ and $m_1 \leq m_2 \leq \ldots \leq m_L$

(iii) Step size condition: $p_{l+1} - p_l \in \{(1,0),(0,1),(1,1)\}$ for $l \in [1 : L-1]$

To obtain an optimal warping path an accumulated cost matrix C from the distance matrix D was calculated. This matrix contains the accumulated costs of warping the template to parts of a movement sequence. The entries can be calculated as follows:

$$\mathbf{C}(0,n) = \mathbf{D}(0,n)\,\forall\, n\ \in \{1,\ldots,N\} \tag{5.2}$$

$$\mathbf{C}(m,0) = \sum_{i=1}^{m} \mathbf{D}(i,0)\,\forall\, m\ \in \{1,\ldots,M\} \tag{5.3}$$

$$\begin{aligned}\mathbf{C}(m,n) = min\{\mathbf{C}(m-1,n-1),\mathbf{C}(m-1,n),\mathbf{C}(m,n-1)\} + \mathbf{D}(m,n)\\ \forall\, m \in \{1,\ldots,M\}, n \in \{1,\ldots,N\}\end{aligned} \tag{5.4}$$

The starting point of the warping path is set to a local minimum of the accumulated costs. Therefore, the distance function $\mathit{\Delta}$ was calculated:

$$\mathit{\Delta} = \mathbf{C}(M-1,n)\,\forall\, n \in \{0,\ldots,N\} \tag{5.5}$$

A criterion to get local minima from $\varDelta$ to select starting points p_0 –which identify good matches between template and reference– is a set threshold τ. Each selected minimum, and consequently the accumulated cost of each selected end point of a stride, has to be smaller than a threshold τ [Bar15]:

$$p_0 = min\{\varDelta\}, \text{ for } p_0 < \tau \tag{5.6}$$

Starting from the detected points p_0 the path can be traced back to get the determining starting point. The threshold is a regulating parameter, the lower the more minima are found. It is set depending on the to be evaluated exercise and is described in detail in the following descriptions of the exercises.

5.5.3 Calculation of the Vertical Jump Height

There are several methods to measure and calculate the height of a vertical jump. With the basic principles of physical science the height can be calculated if the time of flight or the initial velocity are known. The knee sleeve used in this work contains two IMU sensors (described in Section 5.1) including 3D accelerometers, measuring linear acceleration plus gravity.

Measuring the vertical displacement in jumps—calculated by numerical integration of the acceleration data—leads to large errors, as an accelerometer measures all forces working on the object and disturbing the measurement. In particular, there is much noise at the times of take-off and landing which has great influence on integration. Also a constant bias and temperature dependent residual bias in the accelerometer data can lead to a quadratically growing position error. Therefore, the jump height is calculated using the flight time in this work. It is described as time period between take-off and landing. The vertical jump height can be calculated by using the energy conservation approach [Lin01]. This approach states that the total energy of an isolated system is constant during all processes as energy can just be transformed from one to another without any loss. In this context heat energy and friction are neglected and just kinetic energy $\mathrm{E_{kin}}$ and potential energy $\mathrm{E_{pot}}$ are used. Kinetic energy $\mathrm{E_{kin}} = \frac{1}{2}mv^2$ depends on the body movement with body weight m and velocity v. Potential energy $\mathrm{E_{pot}}$ correlates with the spatial collocation of the bodies of a system with gravitational constant $g = 9.81\,\mathrm{m/s^2}$ and height h. Therefore, either the time in the air or the vertical velocity of the center of mass at take-off is needed for the height calculation [Moi08].

A jump can be divided into several phases. In this context only two phases are of importance. Phase 1 describes the initial drop off the ground, phase 2 is the turning point of the body mass in the air at the maximum height. The total energy of both phases are the same according to the energy conservation approach and the kinematic equations:

$$\mathrm{E}_{\mathrm{kin}_1} + \mathrm{E}_{\mathrm{pot}_1} = \mathrm{E}_{\mathrm{kin}_2} + \mathrm{E}_{\mathrm{pot}_2} \tag{5.7}$$

$$\frac{1}{2}mv_1^2 + mgh_1 = \frac{1}{2}mv_2^2 + mgh_2 \tag{5.8}$$

As $h_1 = 0$ and the vertical velocity at the turning point (peak of the jump) is zero (change from positive to negative velocity): $v_2 = 0$.

$$\frac{1}{2}mv_1^2 = mgh_2 \tag{5.9}$$

$$h_{max} = h_2 = \frac{v_1^2}{2g} \tag{5.10}$$

Using this formula the flight height of a jump can be calculated by using the jumper's take-off velocity.
A straightforward method to measure the jump height is to use the time spent in the airborne phase $T = \frac{(t_2 - t_1)}{2}$ with t_1 point in time of take-off and t_2 point in time at landing and the following equation:

$$v_0 = aT = gT \tag{5.11}$$

$$h_{max} = \frac{v^2}{2g} = \frac{(gT)^2}{2 \cdot g} \tag{5.12}$$

$$= \frac{g \cdot \mathit{\Delta} T}{8} \tag{5.13}$$

$$= \frac{1}{8}gT^2 \tag{5.14}$$

The prerequisite for using the formula is based on the assumption that the position of the center of mass at take-off landing coincide [Moi08, Pic11]. A table of the relationship between take-off velocity, vertical jump height and flight time can be found in the Appendix of this thesis (Table C.3).

The video method is considered the „gold standard“ technique and is used as a reference to estimate the vertical jump height [Dia11]. The literature indicates that there are significant differences among vertical jump heights estimated by different methods. Jonathan Ache Dias et al. [Dia11] compared three methods of calculating vertical jump height. They used the video method, which measures the the displacement of the center of mass, as „gold standard“ and compared the calculated jump height (using flight time or double integration) against it. The mean difference of 20 study participants between flight time method and video measure was about 10.33 cm. However, considering that measuring the vertical jump height in our use case, should be done in a practical and objective manner the video method is not feasible. Accelerometer have the disadvantage that even small forces working on the object disturbs the measurement. A doubled integration would lead to a great error in the calculated height. Therefore, the calculation via flight time may be a more viable option and was used within the algorithms.

5.5.4 Exercises

The different exercises were performed following a predefined schedule (see Table 5.2). After each exercise there was a break of about one minute and the collected data was saved. Therefore, each type of exercise is saved in an extra file. Algorithms, based on time-invariant template matching, were developed which extract required events from the inertial sensor signals, such as defined movement patterns and jumps. The algorithms, searching for patterns matching a predefined event template, extracted and analyzed events, counted repetitions and calculated the jump height. The algorithm using SDTW (see Section 5.5.2) was developed using the data of one participant for template generation. It was then applied to the sensor data for the different exercises, so the data of the other participants were used for algorithm evaluation. The workflow of the algorithm using the SDTW is depicted in Figure 5.7.

There are two different kinds of feedback given to the user. First, the result-oriented feedback. It provides information about the deviations from the desired final or partial result. This information can be counted repetitions or jump heights which can be compared to previous results. Second, knowledge-of-performance feedback deals with the movement process, such as the occurrence of dynamic valgus during jumps.

The precondition for an objective analysis of the sensor data are raw data processing algorithms which calculate and provide the results and parameters in a descriptive term.

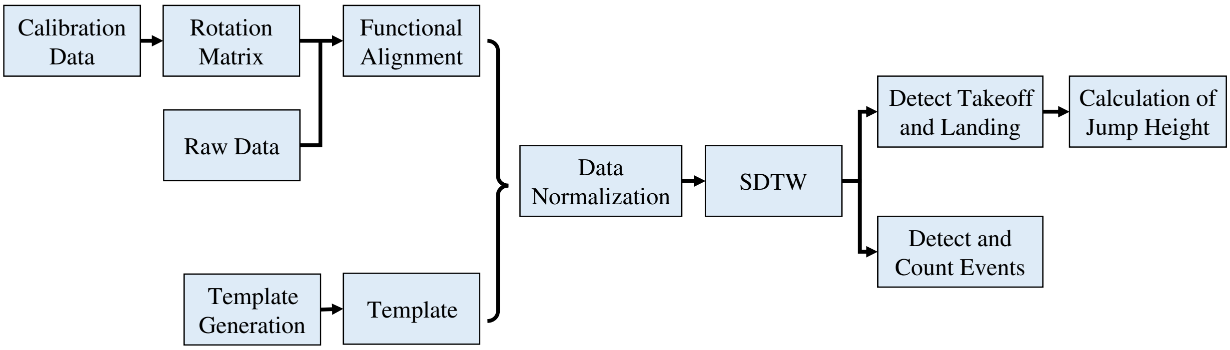


Figure 5.7: Illustration of the algorithm workflow for jump height calculation. Sensor data and exercise template are normalized and by applying the SDTW the jumps can be extracted and the times for take-off and landing detected to calculate the jump height. For drop jumps the ground reaction time is also of great interest, which is defined as the landing time of the drop off the box and the point in time of take-off.

For each exercise accelerometer and gyroscope data of both sensors are saved in a file. Using these raw data the algorithms for the different kinds of exercises were developed.

Single Leg Stand

As already stated in Section 4.2.1 the exercise standing still on the right and left leg respectively is performed in four different ways: on each leg the subject stands still on a firm ground or a folded blanket with eyes open and eyes closed at the second time. The aim of this exercise is to give an assessment about one's balance ability. Therefore, the time has to be stopped as soon as the user loses stability which can be indicated by starting to hop at the place, waving with his arms or touch the ground with the second foot. These movements can be combined as an axial displacement of the center of mass and as center of pressure on the ground which could be measured by the force plate. In this work the time has been stopped using a stopwatch and the results were compared to the requirements.

Glute Bridges and Squats

Glute bridges and squats strengthen knee surrounding muscles and are beneficial for movement control and knee joint stabilization (Section 4.2). Especially the comparison of the single limbs can be a parameter for a stable knee. Therefore, the repetitions of glute bridges and squats performed with both legs and single legs, respectively, are count using SDTW. Thus, Figure 5.7 depicts the rough workflow of the algorithm and Figure 5.8 shows example glute bridge data. As there is only few movement in the lower legs, the data of the sensor attached to the thigh is used.

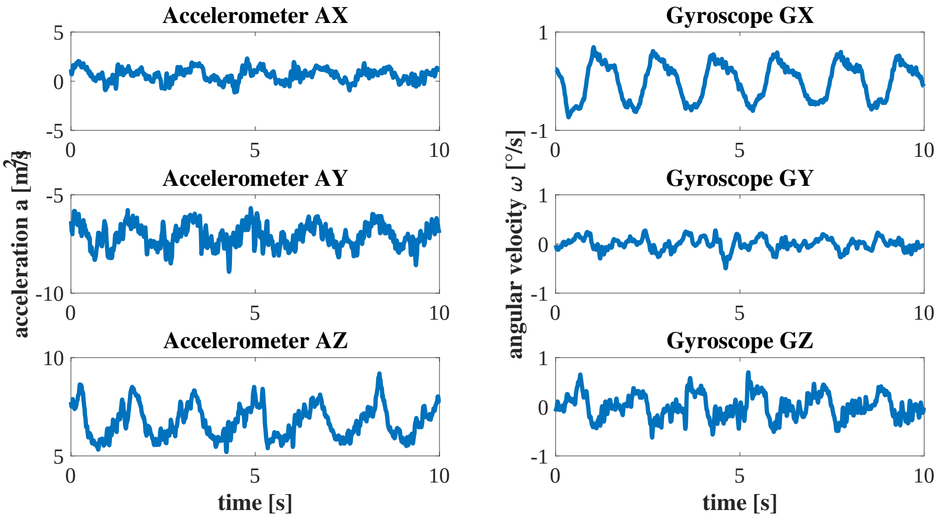


Figure 5.8: Sensor data of 10 s during the glute bridge exercise. The left column shows the accelerometer signals, the right column shows the angular velocity data. Both datasets are of the sensor at the thigh. The angular velocity data GX has been used to detect the single events for this exercise.

To calculate the number of glute bridges the angular velocity data (GX) and for squats the acceleration data (AY) is used. After calculating the rotation matrix the raw data is rotated depending of the to be evaluated leg. A moving average filter is then applied on the data with a window size of 10 by using the existing MATLAB function *tsmovag*. The filtered data is normalized afterwards and the SDTW is applied using a predefined template. The threshold τ was set as the mean of the distance function $\mathit{\Delta}$:

$$\tau = \frac{1}{n} \sum_{i=1}^{n} \mathit{\Delta}_n \tag{5.15}$$

With the use of the threshold τ, signal peaks in the distance matrix data were extracted with conditions of a minimum peak distance of 0.8 s and a minimum peak prominence (mpp) of

$$\text{mpp} = \frac{1}{5}\hat{x}(\mathit{\Delta}),\ \hat{x}(\mathit{\Delta}) \text{ median of distance function.} \tag{5.16}$$

Using the median instead of the mean has the advantage that outliers do not have much influence on the value. This is important as the step for synchronization can be left out. In this way the peaks which fulfill the requirements are counted and represent the number of repetitions.

Jumps

A jump consists of three periods: take-off, flight and landing [Elv07]. The first task is to detect these points in the sensor data. For this purpose several datasets were compared with the appropriate force plate data to identify recognizable features in the data signals. In accordance to the forces the demanded parameters can be extracted and are depicted in Figure 6.1. In the beginning it was tried to detect jump off and landing points using a threshold-based event detection algorithm. Due to the lack of accuracy the SDTW approach was then applied. Measuring jump height can be used as an indirect technique for estimating the muscular strength of the lower extremities. It must be stressed that the height calculation is very sensitive to the initial conditions like initial velocity or airborne time. In this thesis the flight time approach (5.14) was applied. The flight time describes the time interval in which the vertical acceleration was found to be equal or lower gravitational acceleration.

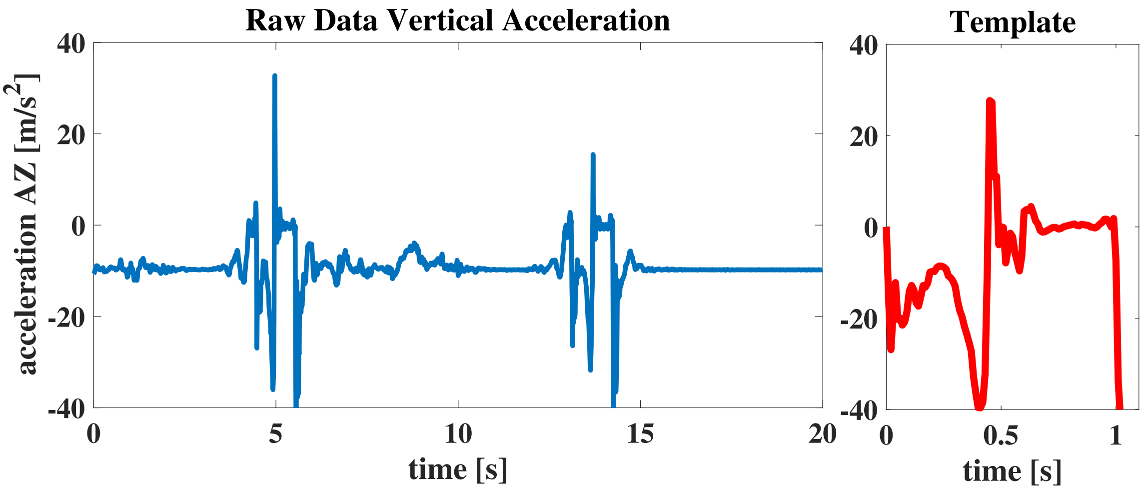


Figure 5.9: An example drop jump sequence and the related template (red) before normalization are shown.

Figure 5.7 shows the algorithm workflow with the individual stages for jump height calculation. In the first instance the calibration data of the subject is used for the functional alignment and to calculate the rotation according to Section 5.5.1. The exercise raw data is then rotated into the global coordinate system and normalized. A previously generated template, which has been manually extracted of one jump, is also normalized. An example drop

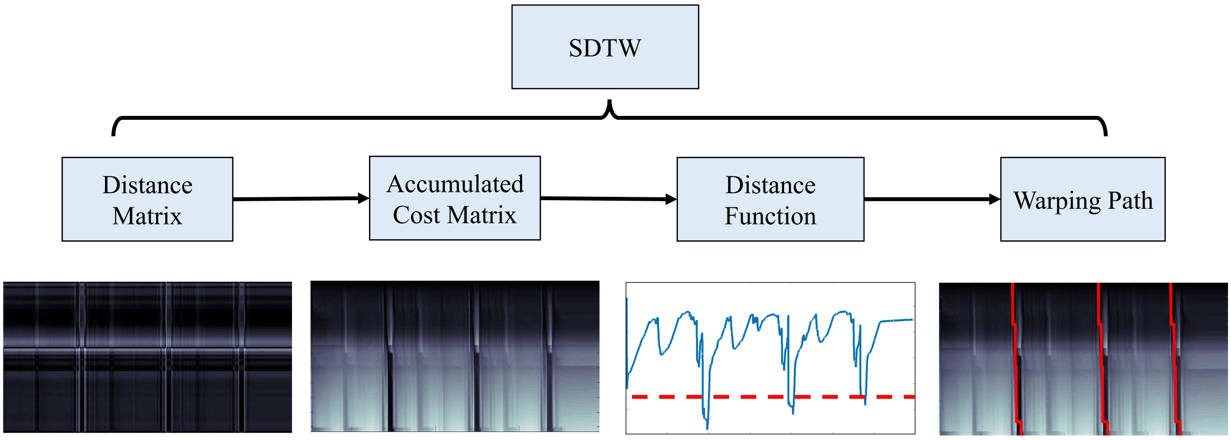


Figure 5.10: Steps of the SDTW process on drop jump data. Based on the aligned vertical acceleration and the previous manually extracted jump template the distance and accumulated cost matrices are calculated. With the use of the distance function and a set threshold (dashed red line) the starting points for the warping paths (solid red lines) can be extracted.

jump sequence and also the template for drop jumps is depicted in Figure 5.9. Applying the SDTW-algorithm the points in time of take-off and landing can be extracted. The individual steps of this process are described in Figure 5.10. The points of landings are extracted using the distance function $\mathit{\Delta}$. The peaks with a minimum height $\tau = \frac{1}{2}(max(\mathit{\Delta}) + min(\mathit{\Delta}))$, minimum distance of 0.5 s and minimum peak prominence $\mathrm{mpp} = \frac{1}{4}|\tau|$ are the distinctive points which represent the landings of the single performed jumps. The warping paths are calculated afterwards to extract the points of take-off. With this time interval of take-off and landing the flight time is calculated using (5.14). In the end detected jumps with a jump height below 0.05 m are deleted to prevent movements which are detected as jumps by mistake. In this way the squat jumps and the single leg squat jumps are analyzed.

The drop jump is a special case were not only take-off and landing but also the drop from the box was detected, so that either flight time h or stance duration ($\mathrm{t_S}$) is extracted. With these two parameters the reactive strength index (RSI) can be calculated by:

$$\mathrm{RSI} = \frac{\mathrm{h}}{\mathrm{t_S}} \tag{5.17}$$

Landing and drop (which marks the initial ground contact after the jump from the box) are extracted in the same way as described above for the squat jump by using the distance function and warping path, respectively. The additional point of the take-off after the drop was detected by using the point of landing and buffering the previous 80 samples, which are data of 0.8 s, to find the most distinctive peak which represents the point of take-off.

Single leg hops

The single leg hops are evaluated by using the gyroscope data (GX) of the sensor attached to the shank. An example data sequence of a single leg hop is shown in Figure 5.11. Depending on the to be evaluated leg the raw data is rotated applying the calibration dataset to calculate the rotation matrix. A manually defined template is extracted of one test subject and the SDTW is applied.The prerequisites to extract the individual hops are a threshold $\tau = \frac{1}{2}(\max(\mathit{\Delta}) + \min(\mathit{\Delta}))$, a minimum peak distance of 0.4 s and a minimum peak prominence of $\mathrm{mpp} = \frac{1}{4}|\tau|$. These values are based on the test dataset from which also the templates have been extracted.

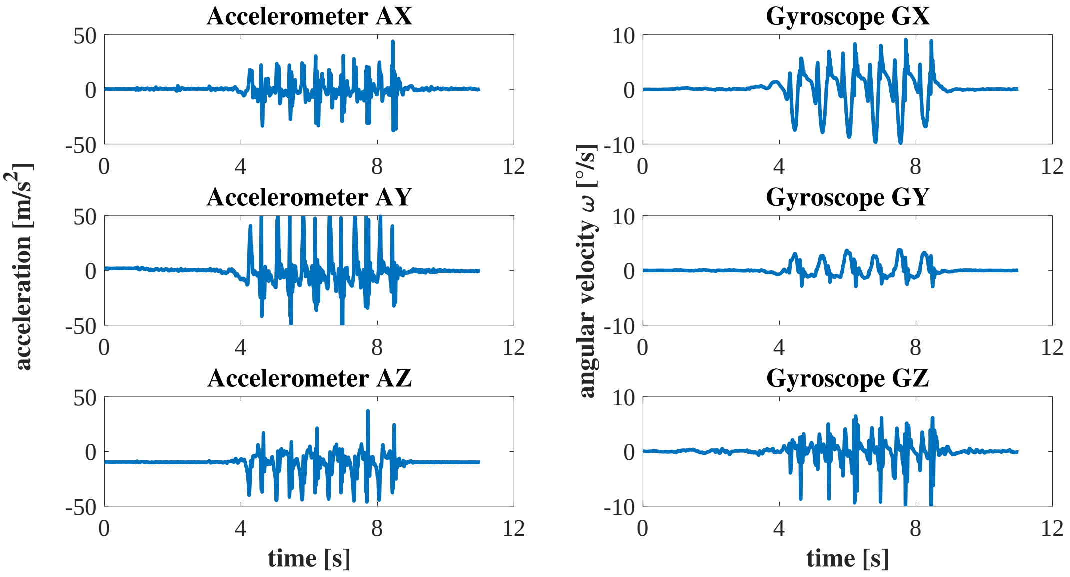


Figure 5.11: Sensor data of a single leg hop sequence performed on the right leg straight on. The left column shows the accelerometer signals, the right column shows the angular velocity data. Both datasets are of the sensor at the lower leg.

5.6 Expert Labeling of the Jump Data

A biomechanical analysis uses two main approaches to analyze human movement patterns in sport: qualitative and quantitative analysis. „Qualitative analysis describes and analyze movements non-numerically, by seeing movements as ’patterns’, while quantitative analysis describes and analyzes movements numerically“ [Bar07]. Qualitative analysis can be video recording or observation but also other movement pattern representations, such as graphs. In contrary quantitative analysis include marker-tracking systems, force plates and other sensor data.

In Section 3.1.2 the relevance of the knee movement and angle in the frontal plane has been described. Effects of an unstable knee during a jump exercise is depicted in Figure 5.12. The subjective impression of a dynamic valgus, which leads to an increased risk for ACL rupture, should be supplemented by the knee rotation about the z-axis. Drop jump tests and one-legged squats are screening tests to identify athletes at risk.

An approach to identify athletes at risk is to label the jump exercises by biomechanical experts and to associate the results at first with the knee position data of the motion capturing system. Subsequently several approaches were applied to get a correlation with the sensor data from the knee sleeve sensors. The aim was to receive a measurement system analyzing the knee movement especially before take-off and at landing of jumps, to give a statement about the dynamic valgus and therefore the knee stability.

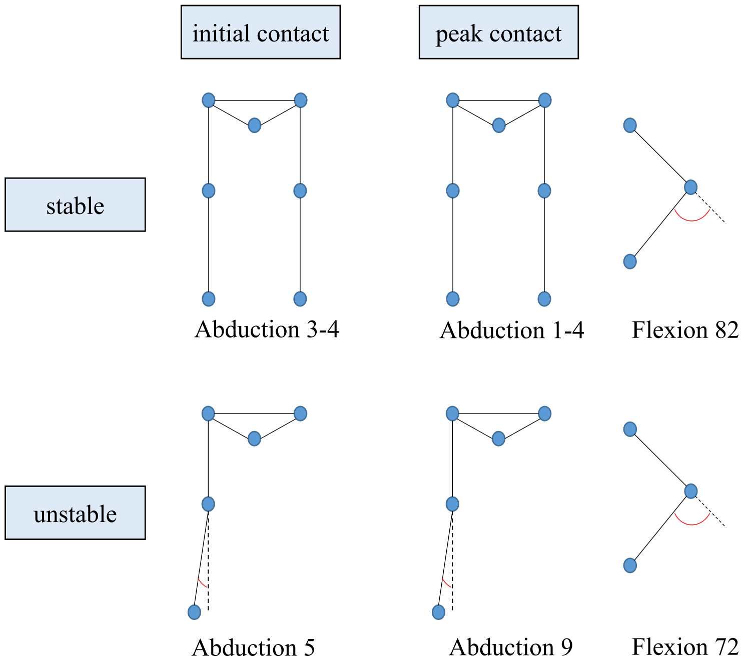


Figure 5.12: During the landing after a jump, a dynamic valgus can occur, increasing the injury risk. The risk can increase in an unstable knee due to a higher tibia abduction. These pictures show the difference of unstable to stable knees in the frontal and sagittal plane. The values of angles are in degree, according to [Hew05].

The movement in the frontal plane of two markers, placed on the medial knee condyles, is analyzed. Considering the dynamic valgus definition of Jöllenbeck et al. [Jöl11], which label a dynamic valgus when the knee moves more than 5 cm medially at landing. As the marker position is synchronized with the force plate data, the times of landing are extracted and the marker position at initial ground contact to 100 ms afterwards is analyzed. With this data the minimal and maximal marker movement in cm can be determined and is compared to the experts subjective impression. A group of four sports and biomechanic experts evaluated the recorded videos of the jumps and analyzed the jumping movement pattern of each participant and provided qualitative feedback. They also evaluated if the test subject has a genu varum, genu valgum or physiologically normal static leg axis depending of full body photos of the standing test subject. For drop jump, squat jump (on both legs), and one-legged squat jumps the jump phases before take-off and at landing are evaluated. The experts marked with a cross conspicuous features regarding the knee movement in the frontal plane at take-off and landing of a jump for the left and right knee. Five possibilities are offered to mark: medial movement (slightly and strong), neutral position, lateral movement (slightly and strong). In addition they evaluated the static impression and if the whole jump was stable or unstable. The assessment sheet is depicted in Appendix D.2. The results of the expert labeling are explained and discussed in Section 6.2 and have been compared afterwards with the calculated data from the quantitative analysis. This method offers a combination of qualitative analysis as a multidisciplinary approach and more objective data.

5.7 Landing Characteristics

Knee movement in the frontal plane, especially while landing after a jump, can cause knee injuries because of the changed force distribution in the knee joint. Mentioning the term time of landing describes the interval of initial foot contact on ground to the point in time of the maximum ground reaction force (GRF). In this section different approaches are presented in order to detect and classify medial and lateral knee movement with the IMU sensor data. Various questions accompany this problem and arise in this context to find a correlation between the terms instability and knee movement. First, the relation between subjective impression of a stable or unstable knee with the knee movement in the frontal plane at landing, is considered. Therefore, the results of the analyzed videos by the expert group were compared with the marker movement from the Vicon system (further details in Section 5.6). The change of the knee position (which can be a combination of lateral-medial-movement and inner-outer-rotation) at landing is important for detecting a dynamic valgus movement which is a risk factor for ACL ruptures. The second question is, if the distinctive data from the reference systems reflect in the sensor data. Therefore, the change in the knee position was compared to the acceleration and angular velocity data. Furthermore, the relation between the knee angle in the sagittal plane (calculated by the Vicon system) and GRF at landing is examined. As there is a correlation between GRF and tibial acceleration data in vertical jumping [Elv07] a possible correlation between FEA and GRF can be transferred to the sensor data. The assumption is, that the higher the GRF the greater the load in the knee joint and its ligament. The angle at landing, which is measurable with the sensors, could offer the users indirect feedback of their loads. This is important as athletes at risk tend to land a jump more upright with a slightly flexed knee and an additional valgus moment [Pet16a]. Several approaches were applied to compare and combine the sensor data with the reference systems to achieve a correlation. The most promising approach is the marker movement in combination with the dynamic valgus and varus movement.

5.8 Statistical Analysis and Methods for the Evaluation

In the descriptive statistics data is collected, processed and analyzed. Large amounts of data is reduced to just a few measures to clearly present complex facts. Hereafter the used measures are explained briefly. The developed algorithms (explained in Section 5.5.4) were applied to the sensor data from the different exercises. The results of the tested sensor data, the numbers of detected events and also the numbers of the manually labeled events can be found in Appendix D. The number of missed events (repetitions, jumps) compared to the signal parts which are wrongly detected as repetitions respectively jumps are evaluated with the following error measurements. The true positives t_p are events that are labeled as such and the detected positives are the recognized ones by the algorithm. The positive-prediction-value (PPV) is the proportion of detected events (true positives t_p and false positives f_p) that are true positive results. A high value indicates the accuracy of the developed algorithm.

$$\mathrm{PPV} = \frac{t_p}{t_p + f_p} \tag{5.18}$$

Also the sensitivity is calculated considering the false negatives f_n, which are the not detected repetitions by the algorithm. Sensitivity indicates the proportion of objects correctly classified as positive on the set of actually positive objects.

$$\text{Sensitivity} = \frac{t_p}{t_p + f_n} \tag{5.19}$$

Arithmetic Mean and Standard Deviation The arithmetic mean $\bar{x}$ describes values of a quantitative characteristic expression and can be calculated as sum of the results x divided by the number of measurements $n \in \mathbb{N}$:

$$\mu = \bar{x} = \frac{1}{n} \sum\nolimits_{i=1}^{n} x_i \tag{5.20}$$

The standard deviation σ is a measure for characterizing a probability distribution and determines how strong the dispersion of the values around an average value is:

$$\sigma = \sqrt{\frac{1}{n} \sum\nolimits_{i=1}^{n} (x_i - \mu)^2} \tag{5.21}$$

Mean Absolute Error The mean absolute error (MAE) is the mean of the absolute values of the absolute difference between the sensor data x_i and the detected parameters y_i [Sam10].

$$\text{MAE} = \frac{\sum_{i=1}^{n} |y_i - x_i|}{n} \tag{5.22}$$

Root Mean Squared Error The mean squared deviation (MSD) is the mean of the squared prediction errors between the sensor data and the detected parameters. The root mean squared error (RMSE) is the squared root of the MSD and sensitive to outliers, as each error on RMSD is proportional to the size of the squared error [Wil05]:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} |y_i - x_i|^2}{n}} \tag{5.23}$$

Relative Error Relative error (RE) and mean relative error MRE in % according to[Cro03].

$$\text{RE} = \frac{\text{measurement - reference}}{\text{measurement}} * 100 \tag{5.24}$$

$$\text{MRE} = \frac{1}{n} \sum\nolimits_{i=1}^{n} |RE_i| \tag{5.25}$$

Bland-Altman-Plot The Bland-Altman-Plot is a statistical method for agreement assession named after J. M. Bland and D. G. Altman [Bla10]. This plot describes the relation between a new method with an established one or a gold standard. In this context the calculated jump heights using the sensor data $\bar{x}_i$ against the values calculated by the force platform x_i are compared. The plot is the average of the two jump heights of each performed jump against the differences of the jump heights. With this schematic representation the relationship between the measurement error and the true value can be determined [Bla10, Bla86, Atk98]. Therefore, the bias is calculated, estimated by the mean difference (μ) and the standard deviation of the differences (σ) [Bla10]. Three denoting horizontal lines supplement the scatter chart. The middle one is the mean difference of the two comparing systems. The upper line and lower one respectively are called limits of agreement (LoA) [Bla10] and can be calculated by

$$\mathrm{LoA} = \mu \pm 1.96\sigma. \tag{5.26}$$

„If the differences are normally distributed, 95% of differences will lie between these limits“ [Bla10]. The advantage of this kind of presentation method provides a visual assessment of the variance of the deviations and also if there are systematic measurement errors.

Chapter 6

Results and Discussion

This chapter covers the results of the applied algorithms on the exercises of the test battery, which are defined in Chapter 4. The methods and results but also limits and possible improvements are discussed. First, the results of the developed algorithms which were applied to the study data, are evaluated and discussed in Section 6.1. Also the extracted parameters were compared to the reference systems. Subsequently, the results of the expert labeling are presented and compared to quantitative data in Section 6.2. Furthermore, Section 6.2, focuses on the landing phases of a jump and its characteristic details and also discuss the previous asked questions from Section 5.7. In the last part, the test battery and the data acquisition procedure are discussed also with regard to the usability of the sensor equipped knee sleeve in Section 6.3.

6.1 Evaluation of the Algorithms

6.1.1 Single Leg Stand

The single leg stand represents the ability to balance. This exercise was also used to gain information about the differences between right and left leg. Additionally, the different grounds were reflected in the results of the participants. Furthermore, it was tried to find divergences between the sensor data standing on firm ground and on a folded blanket to get information about equalizing movements and moreover about the underground. Therefore, the standard deviation of the acceleration and angular velocity data has been used. However, no discernible trend could be observed in the single leg stands of the 16 subjects.

	SLS on firm ground				SLS on folded blanket			
	eyes open		eyes closed		eyes open		eyes closed	
	right	left	right	left	right	left	right	left
mean time $\mu \pm \sigma$ [s]	60 ± 0	56.9 ± 12.1	33.4 ± 22.9	27.6 ± 21.1	60 ± 0	57.3 ± 7.2	24.4 ± 24.3	16.0 ± 11.8
LSI [%]	94.8 ± 20.2		61.6 ± 34.2		95.5 ± 12.0		47.1 ± 24.2	

Table 6.1: Mean times of the single leg stands of both levels and with eyes open and closed, respectively. The LSI for the performance with open eyes is in the normal range, whereas the LSI for exercises with closed eyes is below the threshold.

All but one participants were able to stand on one leg for one minute in the single leg stands with open eyes, independent of the base. To compare the performances of the right and the left leg the formula for MAE (5.22) is used. Standing on firm ground with closed eyes there was a mean absolute difference between right and left leg of 16.3 ± 17.3 s and standing on a blanket the difference was 19.3 ± 19.8 s. There are great differences of the LSI values between open and closed eye performances. The LSI for the performance with open eyes is in the normal range, whereas the LSI for exercises with closed eyes is below the threshold for a stable knee which is 85 %.

Discussion Table 6.1 shows the differences between standing on firm ground and on a folded blanket. The mean time of the participants was lower when standing on a folded blanket as it is more difficult to keep balance on it than on a firm ground. In the questionnaire that was completed after the data acquisition, the test subjects indicated difficulties maintaining the balance standing just on one leg. A further observation was made: during the exercises with closed eyes most of the test subjects successfully maintained the balance until they lost balance due to an acoustic noise (e.g. someone entered the room). In most cases this was a trigger and they lost the balance immediately. To obtain more general results this test should be rerun in a silent room without any disturbances to get equal conditions and a better impression about the results between the participants. This would also explain the differences of the LSI between open and closed eye performance. In comparison to normative data (see Appendix, Table C.1, published by [Spr07]) the participants of this study achieved higher results of duration.

6.1.2 Glute Bridges and Squats

The glute bridge and squat exercises are divided in two parts: the performance on both legs in level I and the single leg versions in level II. Latter may recognize differences between the limbs and are used to calculate the LSI. Table 6.2 shows the statistical analysis of these exercises. In level I, on average the test subjects nearly performed as many glute bridges (26.1 ± 5.9) as squats (26.2 ± 4.7) in one minute. In each exercise the MAE was less than one event, while the values of sensitivity are in the range of 96.7 - 98.6 % and the positive-prediction-values (PPV) are in the range of 97.2 - 99.3 %.

		Glute Bridge	Glute Bridge R	Glute Bridge L	Squats	Squats R	Squats L
Number of test subjects		16	15	15	16	14	14
Total amount of events		418	385	350	419	413	400
MAE		0.50	0.67	0.33	0.88	0.57	0.93
MRE [%]		2.73	4.59	3.15	3.21	1.63	4.29
Sensitivity [%]		98.07	97.40	98.57	96.66	98.06	96.75
PPV [%]		98.80	97.15	98.85	99.26	98.06	99.23
mean LSI [%]	recorded		82.2 ± 9.4			81.4 ± 14.9	
	detected		82.3 ± 9.6			79.7 ± 14.4	

Table 6.2: Calculated values for statistical analysis according to Section 5.8. From the table it can be seen, that more squats than glute bridges were performed. The MRE is 1.63-4.59 % depending on the exercise and all values for sensitivity and PPV are above 96 %. Each calculated mean value is below the threshold of 85 % and declares, according to the definition an unstable knee.

The LSI was calculated for each participant and subsequently averaged. Although there were just small differences in total between right and left leg, the LSI for recorded single leg glute bridges is 82.2 ± 9.4 % and for single leg squats it is 81.4 ± 14.9 %. The LSI values for the detected events are almost in the same range which can be obtained from Table 6.2. With these values the participants are in average below the threshold for a stable knee even though the most individual LSI values lie in the normal range. This is due to the weighting factor, as people with low repetitions have a greater influence on the result because of the fractional amount. The results for each test subject is listed in the Appendix and can be obtained from Table D.2.

Discussion Compared to level I, there is a larger difference between the numbers of single leg glute bridges and single leg squats, showing that there were more squats performed to fatigue although the subjects did the single leg glute bridges before the single leg squats.

A reason for this difference may be that the users were more familiar with squats and the corresponding muscle groups are more trained. Moreover, during the glute bridge exercise, especially the single leg performance, five test subjects got a cramp which led to a stop of the data acquisition.

A comparison between the results of the study and published values (see Table C.2) is not possible, as the performance on both legs was stopped after one minute, regardless of the endurance ability of the test subject.

The participants were introduced how to perform the exercises. For the glute bridges they were also told to keep their knees at a starting FEA of about 100°. As there were no specifications regarding the speed, height or whether the user can touch the ground with the bottom, different performances were observed. To receive a more generalized result for comparing between the test subjects, a speed should be given to set equal conditions. This can be realized by an acoustic feedback which can be integrated in the used smartphone application. A further improvement would be the integration of the FEA to compare this to a previous set range of motion values. A feedback to the user can be given in the form of a vibration signal. Combining the developed algorithm by the use of the FEA can also be beneficial for the squat exercise to make it more universal. Depending of the achieved knee angle the squat would be counted or not.

At the beginning of the squat exercises (in level I and level II) the test subjects performed a strong step on the force plate due to synchronizing reasons. In most cases this step has been recognized as a squatting performance. This is due to the behaviour of the SDTW which stretch or warp the data non-linearly for an optimal fit (Section 5.5.2). Combining the acceleration and angular velocity data may fix this error.

In conclusion it can be said, that there a high accuracy of the developed algorithms for glute bridges and squats has been achieved.

6.1.3 Jumps

For each participant the jump heights of the drop jumps, squat jumps and also for the single leg squat jump on the right and left leg, respectively, were calculated. For the calculation of the height, using the sensor data as well as the force plate, the time-of-flight method was applied. Figure 6.1 shows the correlation between the sensor data and the two used reference systems for one drop jump exemplary. The upper picture displays the vertical movement of the marker attached to the body at the height of the sacrum (estimated as center of mass). On the vertical axis the normalized height and on the horizontal axis the

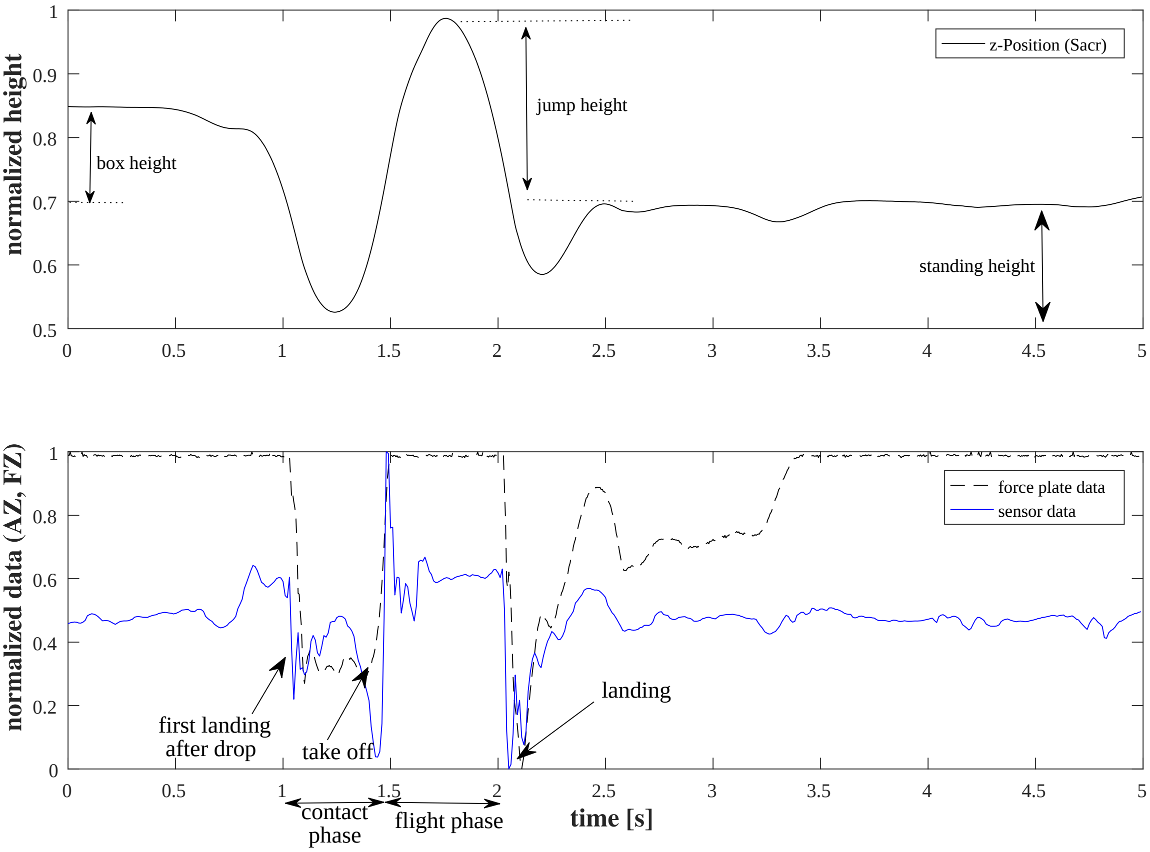


Figure 6.1: Overview of three different kinds of datasets of a drop jump. Top: Vertical position of a motion capturing marker placed on the sacrum as displacement reference. Bottom: Sensor data (vertical acceleration of sensor on thigh) in comparison to the vertical ground reaction force on a force platform, which is considered as gold standard for determining jump height. Also the typical jump phases are marked.

time in seconds is represented. The data plot can be divided in several parts: standing on the box, drop from the box (t = 1 s), contact phase on the ground (t = 1-1.5 s), flight phase of vertical jump (t = 1.5-2 s) and second landing on the ground with built-in force plate (t = 2 s). The illustration below shows the normalized data of vertical acceleration (AZ) from the upper knee sleeve sensor (solid blue line) and the vertical ground reaction force (FZ) recorded by the force plate (dashed black line). The significant points of first landing after drop, take-off and landing as well as the contact phase and flight phase are marked.

In Section 6.2 the results of characterizing and classification the landing are described. For this purpose and also to detect the points in time of landing and take-off the method of subsequence dynamic time warping has been applied to the sensor data. Using this method

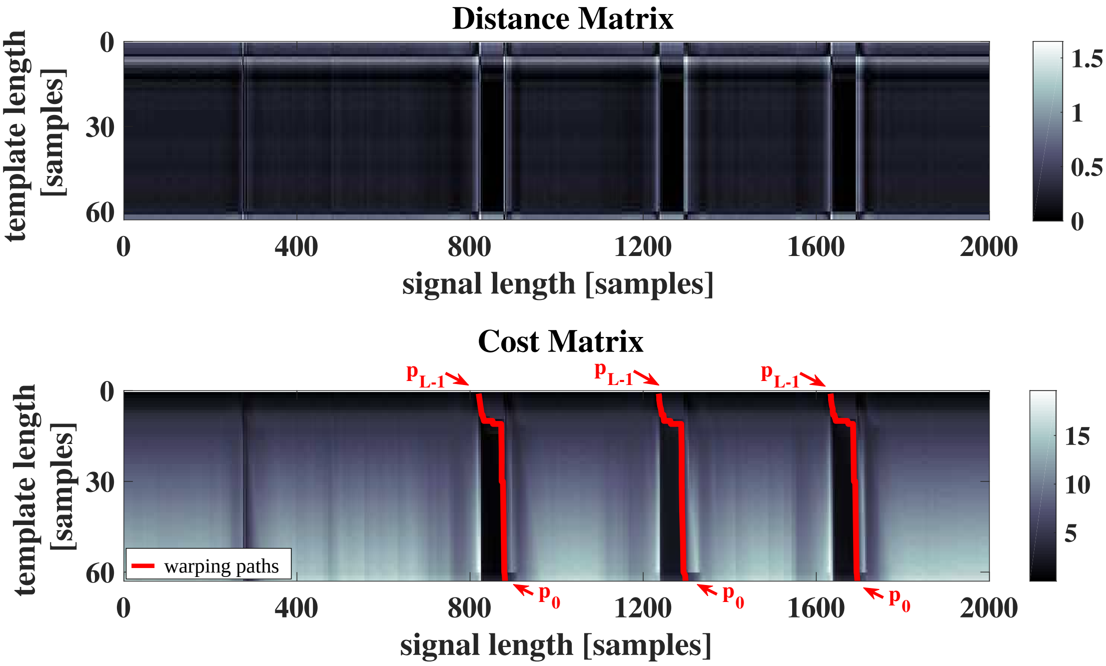
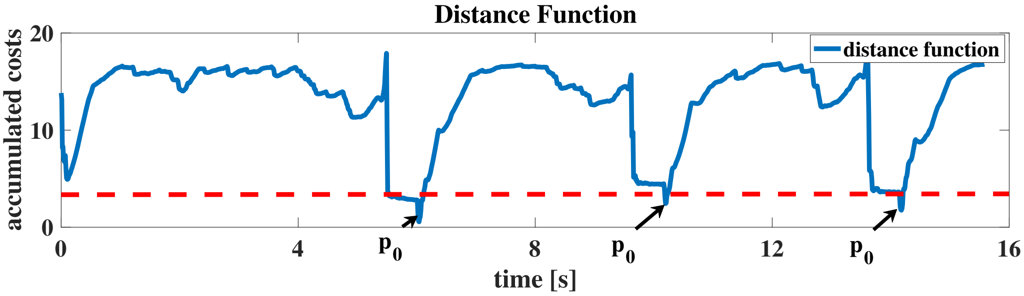


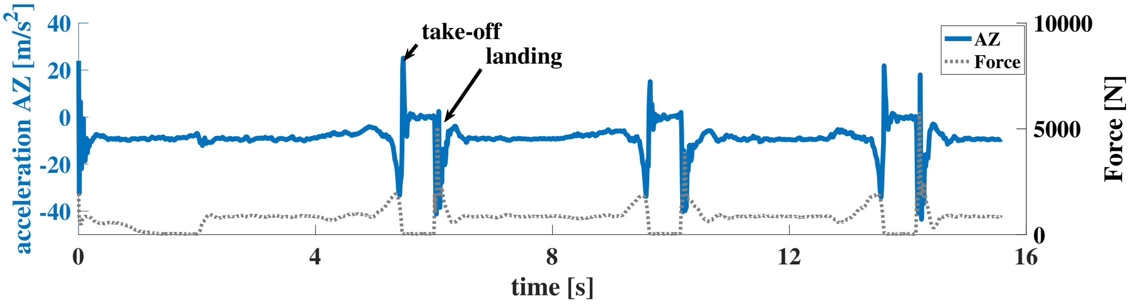
Figure 6.2: Applying the SDTW method on vertical acceleration data including three squat jumps. The upper picture shows the calculated distance matrix **D** with the signal length in samples entered on the x-axis and the template length on the y-axis. The lower one depicts the accumulated cost matrix with the three calculated warping paths (solid red line) with their corresponding starting points p_0.

the single jumps can be detected and the individual jump heights calculated. Figure 6.2 depicts the application of analyzing a dataset of three squat jumps with the SDTW showing the distance and cost matrices. The matrices are set up with the signal length on the x-axis and template length on the y-axis. Also the warping paths (solid red lines) for each jump with the corresponding starting points (p_0) are plotted which indicate the points of landing. The starting points are identified by applying a threshold to the distance function and starting from these points the path with minimum costs is calculated.

For further details Figure 6.3 provides insights to gain better understanding of how the data is evaluated, the jumps are separated and the jump height calculated. Figure 6.3(a) therefore shows the distance function (blue solid line) which is calculated out of the accumulated cost matrix. The horizontal axis represents the time in seconds and the vertical axis the accumulated costs. The red dashed line presents the determined threshold τ. The marked peaks are the starting points p_0 of the warping paths. In Figure 6.3(b) the vertical acceleration (AZ) is plotted as a function of time and the associated ground reaction force.



(a) Distance function with threshold (red) to determine the starting points of the warping paths which also mark the landing points of the jump.



(b) Vertical acceleration (blue), measured by the sensors and ground reaction force (grey) for three squat jumps. Times of take-off and landing are marked for the first jump.

Figure 6.3: Example of a squat jump sequence. Three squat jumps were conducted and detected by determination of significant points in sensor data and using the distance function of the SDTW method. Times of take-off and landing were found and the jump height could be calculated as a result.

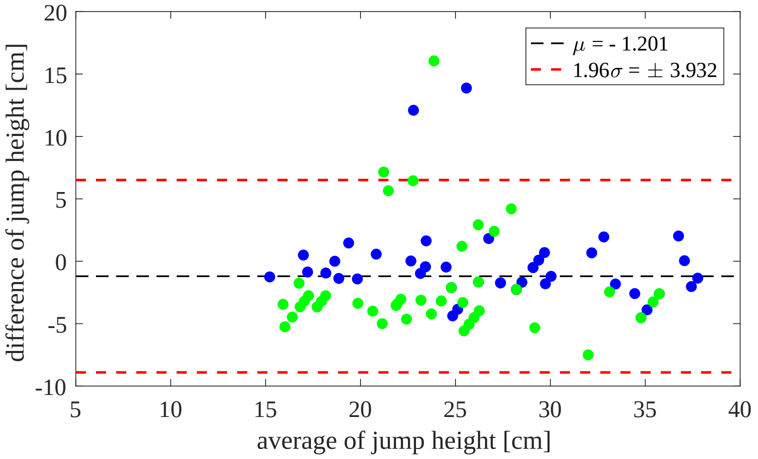


Figure 6.4: Bland-Altman-Plot of the calculated heights from drop jumps (blue) and squat jumps (green) in comparison to the force plate data as reference. The two dashed red lines describe the limits of agreement and the dashed black line presents the mean difference.

For evaluating the calculated jump heights of sensor data they are compared to the jump heights of the force plate data and the results are plotted in two Bland-Altman-Plots: In Figure 6.4 the differences in heights from each subjects performing three drop jumps (blue dots) and squat jumps with both legs (green dots) are plotted. The x-axis represents the average jump height in cm of each analyzed jump and the y-axis shows the difference in cm of each jump height. Figure 6.5 shows the differences in heights from each subject performing three single leg squat jumps on the left and right leg, respectively. Most of the calculated data points lie in the interval of the limits of agreement.

The results of the statistical analysis of the jump heights can be found in Table 6.3. It can be seen that the highest jumps were reached during the drop jumps. The MAE of all jumps lie between 2.1-4.14 cm. For the drop jumps also the ground contact time t_S is calculated to obtain the reactive strength index RSI, using (5.17), which indicates the reactive jump capacity of athletes. The MAE of t_S is 113 ms, however there is only low sensitivity of 81.8 %. The summarized results of the calculated jump heights in comparison with the force plate data are presented in Figure 6.6. Also a regression line with the factor r=0.92 is calculated and plotted. Factor r is the gradient of the regression line and describes the positive linear correlation between the calculated jump height and the reference system.

Discussion With the use of SDTW jumps can be extracted out of one signal and analyzed. The relation between calculated heights out of acceleration data and from GRF is depicted

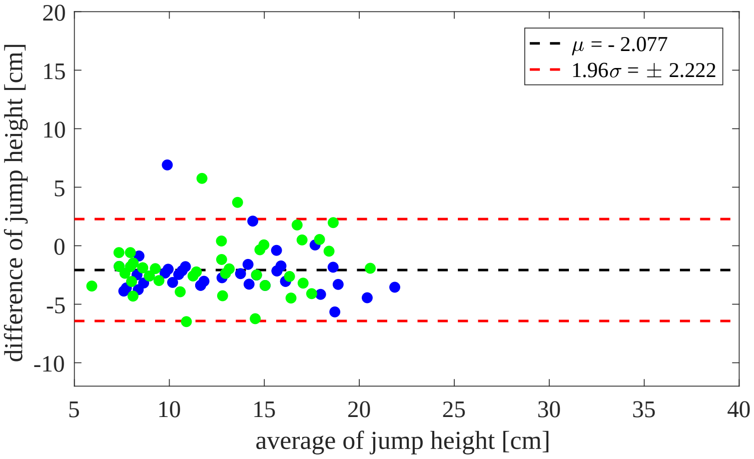


Figure 6.5: Bland-Altman-Plot of single leg jumps right (blue) and single leg jumps left (green) results compared with the jump height calculated by using the force plate.

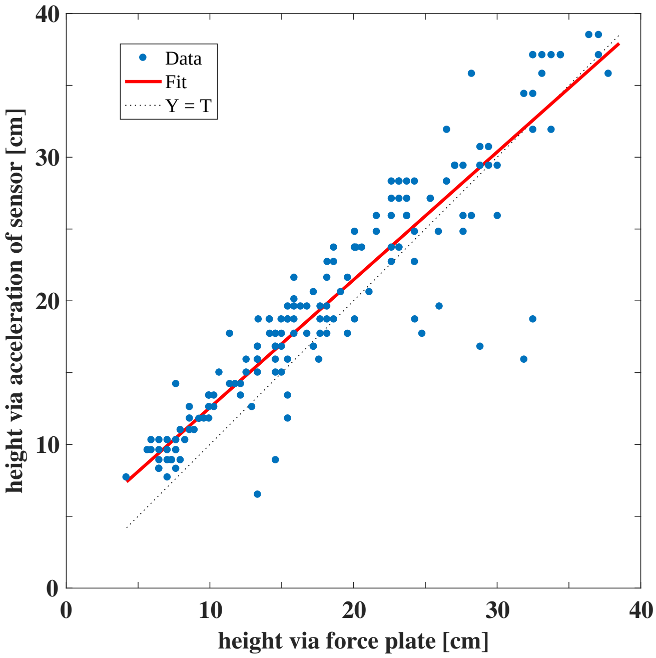


Figure 6.6: Regression plot shows the relation of jump height calculated out of force plate data and sensor data with r=0.9234. The blue data dots represent the individual jumps and the red line the fitted linear regression, with $\text{height}_{\text{acc}} = 0.89 * \text{height}_{\text{force}} + 0.37$.

Jumps				
Statistical Method	Drop Jump	Squat Jump	Squat Jump (single,R)	Squat Jump (single,L)
recorded jumps	48	48	45	45
detected jump	44	43	39	43
mean height $\mu \pm \sigma$ [cm]	26.9 ± 5.8	23.8 ± 6.2	12.3 ± 3.7	12.1 ± 4.5
MAE [cm]	2.10	4.14	3.50	3.65
Sensitivity [%]	91.7	89.6	86.7	95.6

Table 6.3: Statistical Analysis of jump exercises from level I and II.

in Figure 6.6 and besides outliers a linear trend can be seen. A MAE of 2.1-4.14 cm is due to errors in finding the exact take-off and landing time, respectively. The error could be reduced by applying a filter on the raw data to minimize noise which has influence on the detection algorithm. This improvement could also enhance the result for the reaction time t_S which offers more information about the athletes performance. The reaction time marks the time between drop from the box and take-off and is 427 ms in average with a MAE of 113 ms.

Furthermore, the results of calculated jump heights and the sensitivity, in particular, can be enhanced. An overestimated threshold may be the reason for the not detected jumps. As there is only one single jump template used so far for the subsequence dynamic time warping concept the jump data from all but one subject should be averaged. A cross-correlation afterwards could lead to a more general result.

The basic misalignment lies in the fact, that the time of flight is dependent on the initial ground contact which can lead to a deviation of the height from the center of gravity. The equation to calculate the jump height is based on the approval of free-fall to the motion of the center of mass. The used IMUs were fixed in a knee sleeve and therefore not in the body's center of mass. This should be considered when calculating the height out of the IMU data and comparing with reference data coming from a force platform or the motion capturing system. For the calculation of jump height using the flight-time-method it is assumed that the height of the center of mass at take-off and landing coincide. By executing drop jumps and squat jumps this condition rarely occurs and jumper's posture during take-off is different from the instant of landing. Usually the knee joint at take-off is almost extended while at landing it is angled as a gentle treatment for the joint. Therefore, the center of mass is usually lower at landing than at take-off and the height is sometimes overestimated as a result. To achieve this condition of an equal center of mass height at take-off and landing, it is required to keep one's knee fully extended at landing. People who have any difficulties or pain in one knee tend to treat this knee with care and first land with their healthy leg on the ground and with the other one in an angled position which can be a source of error. An improvement of jump height calculation could be realized including the extension-flexion knee angle and also the gyroscope data. This could offer more precise data of the take-off as the knee joint is almost extended as described previously.

6.1.4 Single Leg Hops

The single leg hops are the last exercises in the test battery and serve as indicator for disagreement between the right and left leg of the subjects. They are divided in level I as single leg hops straight on and in level II as crossing performance over a line marked on the ground. An example movement sequence is depicted in Figure 6.7 on the left side and shows the normalized angular velocity GX. The red crosses mark the detected hops. The first seconds before and after the hops the test subject had to stand still to keep the balance. On the right side in the figure the normalized hop template is shown with template length in samples. This manually segmented template of the data from one test subject is used to evaluate either hops straight on or hops crossover the line.

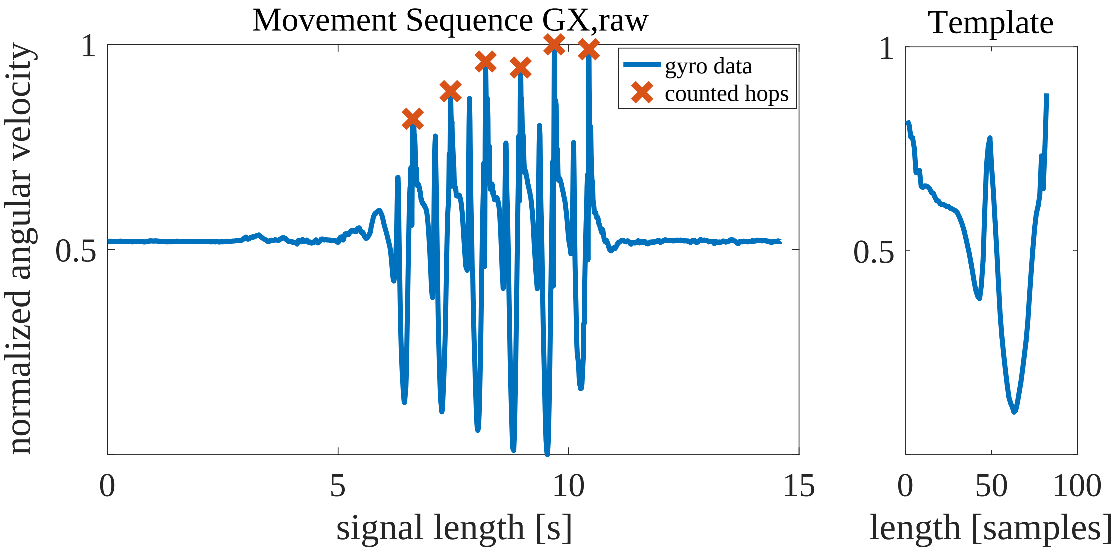


Figure 6.7: Left: Movement sequence of a single leg hop straight on (blue line) performed on the right leg. The time is on the x-axis and the vertical axis shows the angular velocity (GX) of the hops which is filtered with a moving average filter and normalized. In addition, the hops, counted by the algorithm are depicted as red crosses. Right: Hop template for SDTW.

The results of the evaluated hop exercises are in Table 6.4, which shows the accuracy of the algorithm. In total the test subjects needed 9.7 ± 2.1 straight hops on the right leg and 9.9 ± 2.1 on the left leg to cover the 10 m distance. During the crossover hops they needed in average 10.7 ± 2.3 on the right and 10.7 ± 2.2 on the left leg, respectively. As shown in the table the MAE and MRE for the hops on the left leg are lower than the ones from the right leg. The reason could be the template which is different for each side. A more precise result one can get by an averaged template. The values for sensitivity range from 90.97-99.23 % and state the probability to correctly identify hops. The reason for the low sensitivity of SLH straight on the right leg is that the first hop is not detected as real hop in some cases. This is due to the used template which is the third hop of a sequence and therefore differs from the first one. The values for the positive predictive value (PPV) range from 95.92 to 97.73 % and state the number of hops which is the probability that a detected hop is a hop actually. Also the values of the LSI are shown which were calculated for each level and are 90.5 ± 8.0 and 91.1 ± 3.3. The LSI of the detected hops are in average lower but still greater than 85 % which marks the threshold for a stable knee.

Statistical Method		SLH straight R	SLH straight L	SLH crossed R	SLH crossed L
Number of test subjects		16	15	15	13
Total amount of events		165	149	161	130
MAE		0.88	0.33	0.67	0.08
MRE [%]		7.91	4.19	7.15	1.98
Sensitivity [%]		90.97	96.64	93.79	99.23
PPV [%]		95.92	96.00	97.42	97.73
mean LSI [%]	recorded	90.5 ± 8.0		91.1 ± 3.3	
	detected	87.3 ± 15.6		88.9 ± 5.7	

Table 6.4: Statistical analysis of the results for single leg hops of both levels. Also the values of LSI are shown which are calculated for the recorded and also for the detected hops and are all more than 85 %.

Discussion The algorithm for the single leg hops contains the SDTW method to identify the hops. As already stated in Section 6.1.3 there should be an average template of several performed hops which would lead to a more common and more precise result. A source of error are also small hops which were made at the end of the distance. Although the test subjects were encouraged to stand still on the performing leg for after the exercise, several made some hops at the end to maintain the balance. These hops are included in the evaluation and impairs the result. The algorithm can be extended by considering the different signal patterns of straight and crossing performance to distinguish between the two kinds of performances. This may help to figure out if someone has balance problems during the hopping sequence. In other prevention programs the hop tests consist of either hops for distance or a 6 m-timed hop. The covered distance is not measured with the sensor equipped knee sleeve. With the 10 m hop test it is possible to use a hop test which considers the differences between both legs, as it measures the number of hops a person need to achieve the target line. These numbers can be compared using the LSI. In the conducted data acquisition only healthy people participated. This is reflected in the calculated values of the LSI. The leg differences of recorded and also detected hops were in average in the normal range, which is 85-90 %. However athletes with pain or an unstable knee may get problems by achieving the target line of this distance as it is hard to stabilize the pelvis-leg-axis. Limitations of this exercise can be worked out in a study with patients which may also offer a better comparison to the results of the healthy subjects.

6.2 Comparison of Qualitative and Quantitative Analysis of Landing Characteristics

Knee injuries often occur at landing after a jump. For knee injury prevention, especially the occurrence of dynamic valgus movements is important. In this section the results from the video labeling by biomechanical experts in comparison with quantitative data are presented. The videos of the four jump exercises are rated in five stages: strong and slightly medial knee movement, neutral position, strong and slightly lateral knee movement. The results are depicted in Figure 6.8. On the x-axis the five stages are presented and the y-axes represent the marker movement in cm. Each kind of jump is depicted in another color for better clarity. In four of the jumps, the test subject did a sideways hop after landing to maintain balance. As this hop distort the results it has been left out. Negative values for horizontal marker movements characterize a medial motion and positive values a lateral motion. The jump performances, which were rated as neutral reflect the horizontal marker movement around 0 ± 3 cm. Also a trend for lateral and medial motion can be recognized.

Furthermore, the approaches to correlate sensor data with the occurring processes during landing, are presented. The time period from initial ground contact and to the maximum GRF was about 85 ms. Therefore, the data from the initial ground contact (detected by force plate data) for 100 ms has been set as region of interest. In this period the knee movement, knee angles and GRF were considered to refer to the issues and questions which were

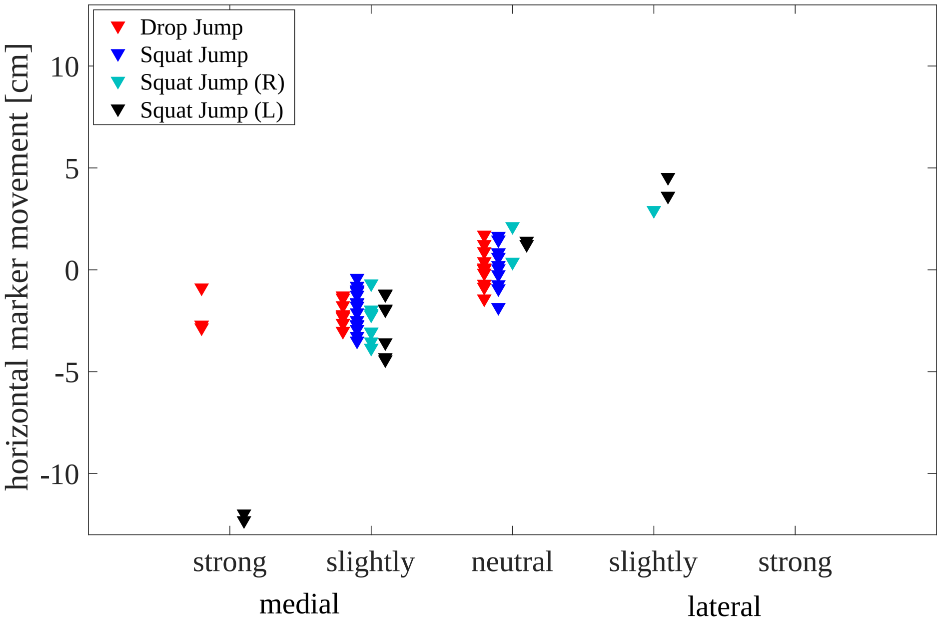


Figure 6.8: Results of expert labeling for the knee movement in the frontal plane during landing after a jump. The marker movement in cm is plotted on the vertical axis and is related to the labeled result of the experts. Values greater than zero show a lateral knee movement while negative values indicate medial knee movement. A correlation between quantitative and qualitative analyzed data can be seen.

defined in Section 5.7. First, the subjective impression of the knee movement is quantified by using the angles and marker positions from the Vicon system and the GRF measured by the force plate. In Figure 6.9 the GRF, which is divided by the corresponding body weight of the test subjects, is plotted against the knee angle (FEA) in the sagittal plane. The red dots mark the values of the left leg and the blue ones the right leg. The values represent the knee angle occurring at the maximum force F_{max} during landing. Although there is a large scattering a trend is recognizable, showing a greater force for smaller extension angles. As the FEA is measurable with the knee sleeve this can offer the user indirect feedback about the load in their knees and they can train to land with more bent knees to reduce stress on their ligaments and reduce injury risk.

The second question addresses the change of knee position from initial ground contact to the maximum GRF as it offers information about the dynamic valgus. This task has already been described and was realized using the Vicon data.

In the following, the sensor data of the knee sleeve has been compared to the reference systems to find a correlation regarding knee movement during landing. It has been considered that performing a dynamic valgus movement, due to an unstable knee, cause higher medial

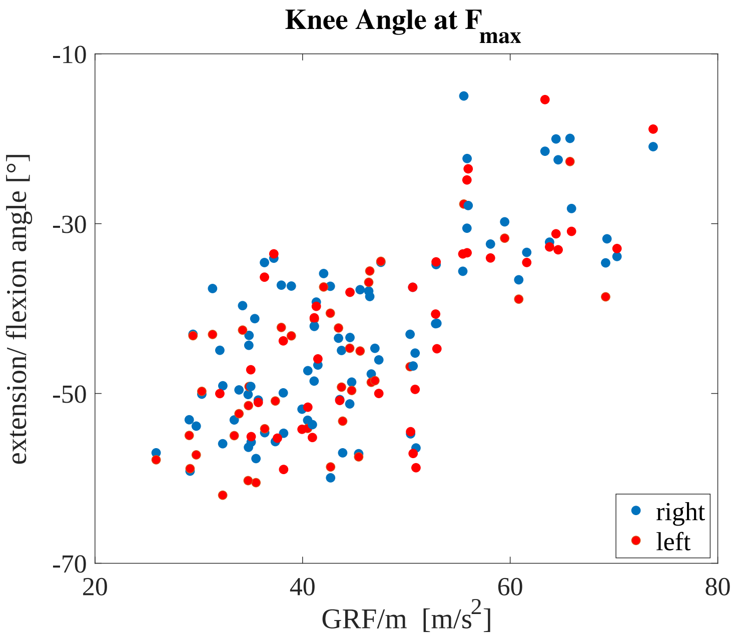


Figure 6.9: Relation between the vertical ground reaction force divided by the corresponding body weights and the extension/ flexion knee angle. It can be seen that the higher the GRF the smaller the angle, so a more bent knee reduces load on the joint and ligaments.

acceleration compared to a stable knee or moving the knee laterally. Also the angular velocity was considered in this task. The angular velocity GY (pronation-supination) from the gyroscope and the acceleration data AX (abduction-adduction) from the accelerometer were compared to the marker positions placed of the medial condyles of the right and left leg. The data during the landing period was analyzed and the mean value and standard deviation were calculated and compared to the range of motion of the marker position. Neither the mean nor the standard deviation were informative to obtain a correlation to the extend of measured knee movement in the frontal plane.

Discussion The analysis from the expert labeling shows a trend, combining dynamic valgus-varus-impression of biomechanical experts with the associated marker movements, although there is no clear dividing line between the various stages. For more precise results there need to be a greater number of experts and also of performed jumps. A further reason for the overlaps can also be the position of the ankles and the opening angles of the feet. When the feet are not placed parallel at landing, the knee movement is altered. A combination between markers placed on the ankles and tip of the shoes could result in

further findings. Nevertheless, a possible correlation between qualitative and quantitative analysis has been shown.
Analyzing the period of landing with the described methods in Section 5.7 is just limited feasible and no clear correlation between the sensor data from the sleeve with the data from the reference systems, regarding the landing characterization, could have been seen. This could be caused by noise in the acceleration data, occurring up to 20 ms after the initial ground contact and distort the results, as the noise has impact on each of the three accelerometer axis. It could be tried to start the measurement after this period of time to evaluate the data and to compare it to the marker positions. Furthermore, an integration of this reduced acceleration data may offer information about lateral or medial knee movement. However, there are further challenges to meet. The sensors are embedded in the knee sleeve which consists of a stretchy material and the movement of muscles and fat tissue influence the signals recorded by the sensors. Especially during jumps there is great movement of tissue which distort the sensor data. A possibility to overcome this could be a sensor which is directly placed on the patella, as there is only few tissue between sensor and bone.

6.3 Evaluation of the Test Battery

The test battery consists of single leg stands, glute bridges, squats, drop jumps, squat jumps and single leg hops in different models of performance depending on the level. This part critically examines the test battery and data acquisition process as a whole and discuss the usability of the knee sleeve.

Test Battery The exercises of the test battery are a combination of a training and progression feedback and can be used as a support during training and as a feedback method. The different components and levels are a suggestion to cover various areas of prevention training and they were chosen to measure several parameters considering knee stability. Therefore, it should be kept in mind, that the program is not a substitute for a balanced and to the athlete adapted training plan. It should rather be considered as assistance for the personal training. The number of repetitions of a given exercise and the comparison to normative data (Appendix C) is not necessarily decisive. The comparison between the healthy and the affected side and the execution is more crucial. That's why the calculated LSI is of great importance. The test battery has several limits as most of the tests are multi-joint exercises. As a result, groups of muscles can compensate weakness which can not be detected with these exercises. The activation of muscles is difficult to measure as there is inter-muscular and intramuscular control and interaction between muscles and proprioceptors. The test set does not offer differentiated results and no quantitative information regarding the isometric muscle tension. The results of the calculated parameters such as counted repetitions neither consider the force-repetition-relation nor repetition-intensity-relation. As a result the calculation of the limb symmetry index (LSI) is limited in its validity and balancing between muscle strength and instability is not simple. Despite these points of criticism the test battery compromises usability and accuracy to offer exercise related feedback to the user.

Data Acquisition For the data acquisition only healthy subjects participated. Nevertheless, six participants who stated in the knee related questionnaire that they feel grinding, hear clicking or any other type of noise when moving their knee. However, they also said that they feel confident and have no difficulties with their knee at all. Five test subjects stopped the single leg glute bridges exercise because they got a muscle cramp. This can lead to errors in calculating the LSI.
To gain more information and to improve the algorithms a study with test subjects who have an unstable knee should be conducted. However, the question arises if they could perform each exercise. Especially the single leg jumps and hops for 10 m may be critical as there is a great load on the knee. A further aspect to prove is the order of the exercises starting with drop jumps, single leg hops, squat jumps, as jumps are most challenging regarding the neuromuscular control. Then squats, glute bridges and single leg stand in the end should be performed. The results should be compared to this study if there is a significant change depending on the exercise order.

Usability As part of the project „Virtual Trainer“ (see Section 2.2) the test battery can be used to make an assessment of one's progress in a given period of time. In this project, there is a great range of different training exercises and the user's progress to the next level depends on function-based milestones. The test set of this work can be an enhancement option to assess the knee stability and user performance. So far, the sensor data is recorded on the SD-card in the microcontroller and the calculations are done afterwards. To provide user-friendly control, the developed algorithms can be enhanced for an automated feedback to the user's smartphone. The prevention tasks take some time during the training session. The challenge is to offer easy to use tools to support the athlete. This is achieved with the sensor equipped knee sleeves, the predefined parameters and the developed algorithms which extract and analyze the region of interests.

Chapter 7

Summary and Outlook

The last chapter of this thesis includes a summary of the procedures and results. It also provides a short outlook with recommendations for improvements and future research.

7.1 Summary

Usually biomechanical analysis is performed and evaluated by experts such as physiotherapists and by using motion capturing systems and force plates. In this work a test battery has been developed based on exercises from knee injury prevention programs. The exercises cover strength and balance tests and also several jump and hop tests and were chosen to reduce the risk for ACL ruptures. A precondition was that the exercise dependent parameters are measurable and evaluable with an existing sensor equipped knee sleeve to provide feedback. This feedback shall serve as assistance at private training sessions to support people feeling uncertain and insecure about their knee.

Two inertial measurement units are embedded in the knee sleeve and the exercises were evaluated depending on acceleration and angular velocity data. After a functional alignment the parameters were extracted by using a SDTW approach. Data templates for the algorithms of the different exercises, were manually extracted from one dataset. For glute bridges, squats and single leg hops exercises, the leg symmetry was determined from the amount of repetitions by calculating the LSI. By extracting the time points of take-off and landing the jump height has been calculated using the time-of-flight method for the jump exercises. The RSI of the drop jumps was also determined.

For evaluating the accuracy of the algorithms a study with 16 healthy participants has been conducted. Each participant performed the complete test battery. Reference systems, such as force plate and a motion capture system served as basis for comparison and evaluation of the experimental results.

For glute bridges and squats the sensitivity of detected events ranges from 96.6-98.6 % and the PPV is 97.2-99.3 %. The MAE for the hops is 0.1-0.9 hops. Depending on the jump exercise and compared to the force plate data, a MAE for jump heights, ranging from 2.1 to 4.1 cm, was achieved. Jumping performance is a possible indicator for knee instabilities. Especially the events of take-off and landing are of great importance to detect potentially risky situations, as an occurring dynamic valgus movement can lead to knee injuries. To obtain an informative value about one's knee stability with the sensor data, the knee movement at landing was compared to the acceleration and angular velocity data from the IMUs. As additional approach, a group of biomechanical experts labeled the videos of the jump exercises from the data acquisition and classified the jumps into stable and unstable. They also evaluated the knee movement in the frontal plane during landing. These results were compared to the knee movement data of the Vicon system and showed a measurable correlation between qualitative and quantitative results.

In conclusion, within this master thesis a new application for a supervised prevention program was developed, including a sensor equipped knee sleeve by which predefined events can be automatically calculated out of acceleration and angular velocity data. The results of the evaluation processes prove that the algorithms, based on SDTW, deliver robust and reliable outcomes. With this promising approach, the user has the opportunity to perform jumps and exercises of the test battery independently to get feedback about his progress in knee stabilization. By now, the occurrence of dynamic valgus movements during the exercises could not be recognized in the sensor data and is a challenge for future work.

7.2 Outlook

The rupture of an ACL can highly affect athletes and also people in their daily living. Prevention programs showed great impact in improving and strengthening knee stabilizing structures and also reducing risk factors. Despite great attention in sport and rehabilitation, prevention training is still not a part in regular training sessions, so the question arises how to make prevention training attractive. The proposed exercises can be included in a structured warm-up before a training session. To offer an incentive, a score can be developed which evaluates and classifies the performed exercises compared to normative data from athletes of the same age and training status and also in form of a self-assessment to track one's progress. This functional knee score may rate the knee stability considering several different movement patterns. Therefore, a data acquisition can be conducted with patients suffering from knee instability to gain knowledge about the influence of an unstable knee on the sensor data. The knee stability score can be evaluated in a clinical two-stage study with patients and healthy participants to compare and to weight the different exercises to a validate score. Manual tests such as Lachmann, Anterior-Drawer-Sign and Pivot-Shift-Test can offer more precise data. Combining manual test results with quantitative data may provide a correlation between clinical positive and sensor data.

The algorithms, presented in this thesis, are a first approach to measure knee stability related parameters in a training aid to get an automated feedback. The IMUs in the used sensor equipped knee sleeve are linked with the microcontroller via cable connections. When these wires of the knee sleeve get caught during movements of the user, the sensor location possibly shifts. As the result of the functional alignment is based on a stable sensor position, the wires should be fixed and sewed into the sleeve. An improvement of the test battery can be achieved by enhancing the developed algorithms. As the single leg stand represents the ability to balance, it is important to detect when the subject does compensatory movements to keep the balance or uses the second foot to stand stable on the ground. This may be achieved by applying a complementary filter on the acceleration and angular velocity data and to detect the times of losing one's balance with a threshold-based approach. Another interesting task is the detection of signs of fatigue in the sensor data. An analysis of combined acceleration and angular velocity data, during glute bridge exercises to fatigue, may provide a new approach. In the presented algorithm the angular velocity is evaluated to count the repetitions. In addition to this, changes in the acceleration data in the course of time could provide information about one's fatigue which is also a risk factor for ACL ruptures and by this a worthwhile topic to be investigated.

Appendix A

Knee Injury Prevention Programs

First Author	Sample Size	Sex	Age	Program Components	ACL Injury
Walden (2012)	4,564	Female	High School	P, B, S/R, R/T	0.433 (0.175, 1.072)
LaBella (2011)	1,492	Female	High School	P, S/R, R/T	0.164 (0.025, 1.080)
Gilchrist (2008)	1,435	Female	Older than High School	P, S/R, R/T, S	0.584 (0.182, 1.878)
Pasanen (2008)	457	Female	Older than High School	P, B, S/R, S, R/T	1.161 (0.315, 4.274)
Steffen (2008)	2,020	Female	High School	P, B, S/R, R/T, S	0.792 (0.120, 5.205)
Pfeiffer (2006)	1,439	Female	High School	P,R/T	2.153 (0.321, 14.447)
Mandelbaum (2005)	2,946	Female	High School	P, S/R, R/T, S	0.114 (0.018, 0.723)
Petersen (2005)	276	Female	Older than High School	P, B, R/T	0.190 (0.014, 2.523)
Olsen (2005)	1,837	Female, Male	High School	P, B, S/R, R/T,	0.280 (0.045, 1.747)
Myklebust (2003)	1,797	Female	Older than High School	P,B,R/T	0.960 (0.491, 1.875)
Heidt (2000)	300	Female	High School	P, S/R, R/T	0.125 (0.016, 0.999)
Sodermann (2000)	140	Female	Older Than High School	B	5.492 (0.434, 69.533)
Hewett (1999)	829	Female	High School	P, S/R, R/T, S	0.537 (0.055, 5.251)
Caraffa (1996)	600	not reported	Older than High School	B	0.143 (0.064, 0.321)

Table A.1: Knee Injury Prevention Programs, according to ([DF15]): P: plyometric (jump training); B: balance exercises; S/R: strength/ resistance training; R/T: running/ technique training exercises (e.g. shuttle run, bounding run, etc.); S: stretching.

Appendix B

Patents

Motion tracking system with inertial-based sensing units

Patent Number	WO 2014150961 A1
Date	25. Sept. 2014
Inventors	Mohamed R. Mahfouz, Gary To
Applicant	Jointvue, Llc
Abstract	Systems, apparatus, and method of monitoring a position of a joint. An inertial monitoring unit is configured to be coupled to a portion of a patient, such as a thigh. Another inertial monitoring unit is configured to be attached to another portion of the patient, such as a shank, that is connected to the other portion by a joint, such as a joint. The inertial monitoring units detect motion of their respective portions of the patient and transmit data indicative of this motion. These transmissions may be received by a computer and used to determine an orientation of the joint. The inertial monitoring units may also be coupled to vibration detection modules and/or ultrasound modules that provide additional data regarding a condition of the joint.

Dynamic injury protection system

Patent Number	WO 2016161457 A1
Date	6. Oct. 2016
Inventors	Chadley Guerrier
Applicant	Chadley Guerrier
Abstract	A dynamic injury protection system and method for monitoring tissue activity surrounding a joint and automatically supporting the movement of the joint to prevent injuries to and around the joint in response to the monitored activity. The dynamic injury protection system and method is implemented through a protective sleeve assembly having a sleeve base, sensor system, control system, and locking mechanism. When in place on a target joint, the sensor system operates to assess the activity of tissue surrounding the target knee and generate electrical signals corresponding to the tissue activity while the control system selectively causes the locking system the sleeve base to restrict movement of the target joint based on a comparison of assess activity and threshold baselines. Accordingly, the protective sleeve assembly operates to automatically initiate a protective movement restriction on a target joint wherever a dangerous level of stress is sensed.

Apparatus for monitoring the range of motion of a joint

Patent Number	EP 1938749 A2
Date	2. July 2008
Inventors	Sherrod A. Woods, Thomas J. Sullivan, Robert S. Hastings, Jason T. Sherman, Edward J Caylor Iii
Applicant	DePuy Products, Inc.
Abstract	A system for monitoring the range of motion of a patient's knee includes a knee sleeve, a number of sensor circuits coupled to the knee sleeve, and a communication circuit coupled to the knee sleeve and electrically coupled to the sensor circuits. Each sensor circuit includes a sensor configured to generate data indicative of the position of the respective sensor. The communication circuit is configured to wirelessly transmit the data to a computer.

Appendix C

Normative Data

Age	Gender	eyes open	eyes closed
18-39	male (n=54)	43.2	10.2
	female (n=44)	43.5	10.2
40-49	male (n=51)	40.1	7.3
	female (n=47)	40.4	7.4
50-59	male (n=48)	38.1	4.5
	female (n=50)	36.0	5.0
60-69	male (n=51)	28.7	3.1
	female (n=50)	25.1	2.5

Table C.1: Normative data for single leg stand with eyes open respectively closed on firm ground. The numbers are mean values of three trials in seconds. Data from [Spr07].

	Male	Female
Un-trained	0.6	0.5
Novice	1.2	1.0
Intermediate	1.5	1.2
Advanced	2.0	1.6
Elite	2.7	2.2

Table C.2: Normative data for double leg squats. Division of body weight with realized number of squat. Example: A man weighs 75 kg and is able to do 90 squats, then he is „novice“. Data from [Com12].

take-off velocity (m/s)	**vertical jump height** (cm)	**flight time** (s)
0.981	4.9	0.2
1.226	7.7	0.25
1.472	11.0	0.3
1.717	15.0	0.35
1.962	19.6	0.4
2.207	24.8	0.45
2.453	30.7	0.5
2.698	37.1	0.55
2.943	44.1	0.6
3.188	51.8	0.65
3.434	60.1	0.7
3.679	69.0	0.75
3.924	78.5	0.8
4.169	88.6	0.85
4.415	99.3	0.9
4.659	110.6	0.95

Table C.3: Dependencies of take-off velocity, vertical jump height and flight time using formulas 5.10 and 5.14, values according to [McL07].

	Professional Players	Junior Players	Students
Dominant limb [cm]	28.4 ± 5.5	25.2 ± 4.2	20.5 ± 3.7
Nondominant limb [cm]	25.0 ± 5.3	25.2 ± 4.3	21.2 ± 3.1
Bilateral difference	12.0 ± 7.9	-1.4 ± 7.5	-4.1 ± 11.6

Table C.4: Normative data for drop jumps according to [Sch09].

Appendix D

Data Acquisition

Information

Dear Volunteer

Thank you for participating in this study concerning

Non-invasive Biosignal Analysis for Sports and Movement

Contact Person

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Details about the study

The Digital Sports and Health Lab (Pattern Recognition Lab, Friedrich-Alexander-University Erlangen-Nuremberg) deals with the sensor-based application of pattern recognition algorithms in the area of sports and health. The used devices are small, light-weight and non-invasive and include, for example, motion sensors (accelerometer, gyroscope, magnetometer), physiological sensors (electrocardiogram (ECG), electromyogram (EMG), electroencephalogram (EEG)) and Head-Mounted Displays (Virtual-Reality Glasses, Augmented Reality Glasses). In some cases, video data has to be captured as a reference for the evaluation and validation of the developed applications. The results of the analysis are an important aspect of the creation of athlete-support-systems.

The generation and analysis of new data is essential for the implementation and evaluation of new algorithms. The devices are, for example, integrated into clothes or fixed to the body using a variety of methods. It is planned to place the devices, for example, at the following positions:

- upper and lower limbs,
- torso,
- hip or
- head.

The devices are placed in such a way that they should not influence the participants’ movement. There is no danger due to the use of these devices.

All activities are performed in a laboratory or under real conditions, outside the laboratory. Possible activities include:

- walking
- ascending and descending stairs
- jogging
- running
- swimming
- rope jumping
- bicycling
- isolated movements of single muscle groups or
- other typical body movements.

Profile of Subject

Surname ____

First name ____

Street ____

ZIP / City ____

Telephone ____

E-Mail ____

Date of birth ________________________________

Sex male ☐ female ☐

Body height [cm] ________________________________

Body weight [kg] ________________________________

Size of shoe [EUR] ________________________________

Dress size [S, M, L, XL] ________________________________

Chest width [cm] ________________________________

Handedness right ☐ left ☐

Physical Activity Readiness Questionnaire (PAR-Q)

For most people, physical activity should not pose any problem or hazard. The PAR-Q is designed to identify the small number of adults for whom physical activity might be inappropriate or those who should seek medical advice concerning the type of activity most suitable for them.

Please read the 7 questions below carefully and answer each one honestly: check YES or NO	**YES**	**NO**
1. Has your doctor ever said that you have a heart condition ☐ OR high blood pressure ☐ ?	☐	☐
2. Do you feel pain in your chest at rest, during your daily activities of living, **OR** when you do physical activity?	☐	☐
3. Do you lose balance because of dizziness **OR** have you lost consciousness in the last 12 months? Please answer **NO** if your dizziness was associated with over-breathing (including during vigorous exercise)	☐	☐
4. Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)? **PLEASE LIST CONDITION(S) HERE:**______________________________	☐	☐
5. Are you currently taking prescribed medications for a chronic medical condition? **PLEASE LIST CONDITION(S) AND MEDICATIONS HERE:**____	☐	☐
6. Do you currently have (or have had within the past 12 months) a bone, joint, or soft tissue (muscle, ligament, or tendon) problem, that could be made worse by becoming more physically active? Please answer **NO** if you had a problem in the past, but is ***does not limit your current ability*** to be physically Active. **PLEASE LIST CONDITION(S) HERE:** ____	☐	☐
7. Has your doctor ever said that you should only do medically supervised physical activity?	☐	☐

If you answered **NO** to all questions above, you are cleared for physical activity. Go to **Page 7** to sign the Participant Declaration. You do not need to complete the question on **PAGES 5 and 6.**

If you answered **YES** to one or more of the questions above, complete **PAGE 5 and 6.**

Follow Up Questions

1. Do you have Arthritis, Osteoporosis, or Back Problems?

If the above condition(s) is/are present, answer questions 1a-1c If **NO** ☐ go to question 2

1a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments)	**YES** ☐	**NO** ☐
1b. Do you have joint problems causing pain, a recent fracture or fracture caused by osteoporosis or cancer, displaced vertebra (e.g., spondylolisthesis), and/or spondylolysis/pars defect (a crack in the bony ring on the back of the spinal column)?	**YES** ☐	**NO** ☐
1c .Have you had steroid injections or taken steroid tablets regularly for more than 3 months?	**YES** ☐	**NO** ☐

2. Do you currently have Cancer of any kind?

If the above condition(s) is/are present, answer questions 2a-2b If **NO** ☐ go to question 3

2a. Does your cancer diagnosis include any of the following types: lung/bronchogenic, multiple myeloma (cancer of plasma cells), head, and/or neck?	**YES** ☐	**NO** ☐
2b. Are you currently receiving cancer therapy (such as chemotherapy or radiotherapy)?	**YES** ☐	**NO** ☐

3. Do you have a Heart or Cardiovascular Condition? *This includes Coronary Artery Disease, Heart Failure, Diagnosed Abnormality of Heart Rhythm*

If the above condition(s) is/are present, answer questions 3a-3d If **NO** ☐ go to question 4

3a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments)	**YES** ☐	**NO** ☐
3b. Do you have an irregular heart beat that requires medical management? (e.g., atrial fibrillation, premature ventricular contraction)	**YES** ☐	**NO** ☐
3c. Do you have chronic heart failure?	**YES** ☐	**NO** ☐
3d. Do you have diagnosed coronary artery (cardiovascular) disease and have not participated in regular physical activity in the last 2 months?	**YES** ☐	**NO** ☐

4. Do you have High Blood Pressure?

If the above condition(s) is/are present, answer questions 4a-4b If **NO** ☐ go to question 5

4a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments)	**YES** ☐	**NO** ☐
4b. Do you have a resting blood pressure equal to or greater than 160/90 mmHg with or without medication? (Answer YES if you do not know your resting blood pressure)	**YES** ☐	**NO** ☐

5. Do you have any Metabolic Conditions? *This includes Type 1 Diabetes, Type 2 Diabetes, Pre-Diabetes*

If the above condition(s) is/are present, answer questions 5a-5e If **NO** ☐ go to question 6

5a. Do you often have difficulty controlling your blood sugar levels with foods, medications, or other physician-prescribed therapies?	**YES** ☐	**NO** ☐
5b. Do you often suffer from signs and symptoms of low blood sugar (hypoglycemia) following exercise and/or during activities of daily living? Signs of hypoglycemia may include shakiness, nervousness, unusual irritability, abnormal sweating, dizziness or light-headedness, mental confusion, difficulty speaking, weakness, or sleepiness.	**YES** ☐	**NO** ☐
5c. Do you have any signs or symptoms of diabetes complications such as heart or vascular disease and/or complications affecting your eyes, kidneys, OR the sensation in your toes and feet?	**YES** ☐	**NO** ☐
5d. Do you have other metabolic conditions (such as current pregnancy-related diabetes, chronic kidney disease, or liver problems)?	**YES** ☐	**NO** ☐
5e. Are you planning to engage in what for you is unusually high (or vigorous) intensity exercise in the near future?	**YES** ☐	**NO** ☐

6. Do you have any Mental Health Problems or Learning Difficulties? *This includes Alzheimer’s, Dementia, Depression, Anxiety Disorder, Eating Disorder, Psychotic Disorder, Intellectual Disability, Down Syndrome*

If the above condition(s) is/are present, answer questions 6a-6b If **NO** ☐ go to question 7

6a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	**YES** ☐	**NO** ☐
6b. Do you have Down Syndrome AND back problems affecting nerves or muscles?	**YES** ☐	**NO** ☐

7. Do you have a Respiratory Disease? *This includes Chronic Obstructive Pulmonary Disease, Asthma, Pulmonary High Blood Pressure*

If the above condition(s) is/are present, answer questions 7a-7d If **NO** ☐ go to question 8

7a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	**YES** ☐	**NO** ☐
7b. Has your doctor ever said your blood oxygen level is low at rest or during exercise and/or that you require supplemental oxygen therapy?	**YES** ☐	**NO** ☐
7c. If asthmatic, do you currently have symptoms of chest tightness, wheezing, labored breathing, consistent cough (more than 2 days/week), or have you used your rescue medication more than twice in the last week?	**YES** ☐	**NO** ☐
7d. Has your doctor ever said you have high blood pressure in the blood vessels of your lungs?	**YES** ☐	**NO** ☐

8. Do you have a Spinal Cord Injury? *This includes Tetraplegia and Paraplegia*

If the above condition(s) is/are present, answer questions 8a-8c If **NO** ☐ go to question 9

8a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	**YES** ☐	**NO** ☐
8b. Do you commonly exhibit low resting blood pressure significant enough to cause dizziness, light-headedness, and/or fainting?	**YES** ☐	**NO** ☐
8c. Has your physician indicated that you exhibit sudden bouts of high blood pressure (known as Autonomic Dysreflexia)?	**YES** ☐	**NO** ☐

9. Have you had a Stroke? *This includes Transient Ischemic Attack (TIA) or Cerebrovascular Event*

If the above condition(s) is/are present, answer questions 8a-8c If **NO** ☐ go to question 10

9a. Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	**YES** ☐	**NO** ☐
9b. Do you have any impairment in walking or mobility?	**YES** ☐	**NO** ☐
9c. Have you experienced a stroke or impairment in nerves or muscles in the past 6 months?	**YES** ☐	**NO** ☐

10. Do you have any other medical condition not listed above or do you have two or more medical conditions?

If the above condition(s) is/are present, answer questions 10a-10c If **NO** ☐ read page 7

10a. Have you experienced a blackout, fainted, or lost consciousness as a result of a head injury within the last 12 months **OR** have you had a diagnosed concussion within the last 12 months?	**YES** ☐	**NO** ☐
10b. Do you have a medical condition that is not listed (such as epilepsy, neurological conditions, kidney problems)?	**YES** ☐	**NO** ☐
10c. Do you currently live with two or more medical conditions?	**YES** ☐	**NO** ☐

Please list your medical condition(s) ____
and any related medications here: ____

Assumption of Risk

I hereby state that I have read, understood and answered the questions above honestly. I also state that I wish to participate in all the activities mentioned in *details about study*. I realize that my participation in these activities involves the risk of injury. I hereby confirm that I am voluntarily engaging in an acceptable level of activity, which has been recommended to me.

In addition

All of my additional questions were answered to my complete satisfaction.

On the part of the university no insurance protection exists for the participant.

Erlangen, the ______________________________________

Signature of participant ______________________________________

Erlangen, the ______________________________________

Signature of advisor ______________________________________

Agreement for Participation in the Study

With your signature you confirm the following statements:

- The content of the study was completely explained to me.
- I read and understood the section *details about study*.
- All of my additional questions were answered so that I was completely satisfied.
- I agree to participate in the mentioned study.
- The participation in the study is voluntarily.
- I know that I can cancel the agreement for participation at any time.

Data protection statement:

I hereby agree that the acquired data (including video) and the personal data can be used for scientific research. The acquired data will be treated in an anonymous manner (i.e. the mapping to your name is only possible with utilities like a reference list, faces in videos will be black barred). The acquired data can be used for

- this study
- further studies or publications.

The acquired data can be disclosed to third parties in an anonymous manner. The agreement can be canceled at any time and without the specification of reasons.

Withdrawal of the agreement for data usage:

I know that I can withdraw my agreement for data usage at any time and without any reason.

In case of withdrawal, I agree that the data will be saved for control purposes.

I have the right to demand deletion.

I know that, in case of anonymous storage, the requested deletion of the data is not possible.

Erlangen, the ________________________________

Signature of participant ________________________________

Erlangen, the ________________________________

Signature of advisor ________________________________

Data Acquisition

Name ________________________________

Date ________________________________

Do you have any knee problems and/ or did you have any difficulties with your knee in the last 9 months?
This includes pain, swelling, constraints in everyday life and an instable feeling.

a. Did you experience any knee pain in the last two weeks?	**YES** ☐	**NO** ☐
b. Do you have swelling in your knee?	**YES** ☐	**NO** ☐
c. Do you feel grinding, hear clicking or any other type of noise when your knee moves?	**YES** ☐	**NO** ☐
d. Does your knee catch or hang up when moving?	**YES** ☐	**NO** ☐
e. Can you straighten your knee fully?	**YES** ☐	**NO** ☐
f. Can you bend your knee fully?	**YES** ☐	**NO** ☐

g. How much are you troubled with lack of confidence in your knee?
Give a number between 1 (not at all) and 5 (extremely). **1** ☐ **2** ☐ **3** ☐ **4** ☐ **5** ☐

h. In general, how much difficulties do you have with your knee?
Give a number between 1 (not at all) and 5 (extremely). **1** ☐ **2** ☐ **3** ☐ **4** ☐ **5** ☐

i. Have you ever had any knee injuries (e.g. ACL rupture)?
If yes, please describe what kind of injury and when it happened.
____

In addition to the data from the sensors and the motion capture system, videos of the exercises are recorded. These will be evaluated by three medical experts who assess personal knee stability. The videos are not passed on to others than the defined experts and there is no other use of the videos outside this master thesis.

Signature ________________________________

FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

DIGITAL
SPORTS

Data Acquisition

Name ________________________________

Date ________________________________

Please read the questions below carefully and answer each one honestly: check YES or NO

Did you feel any pain and/ or difficulties while doing the following exercises? If you answer one of the following questions with 'yes', please add on which side the pain occurred.				**YES**	**NO**
1.1	Single leg stand, eyes open, right leg			☐	☐
1.2	Single leg stand, eyes open, left leg			☐	☐
1.3	Single leg stand, eyes closed, right leg			☐	☐
1.4	Single leg stand, eyes closed, left leg			☐	☐
1.5	Glute Bridge (both legs)	right leg ☐	left leg ☐	☐	☐
1.6	Squats (both legs)	right leg ☐	left leg ☐	☐	☐
1.7	Drop Jumps	right leg ☐	left leg ☐	☐	☐
1.8	Squat Jumps	right leg ☐	left leg ☐	☐	☐
1.9	Single leg hops straight on, right leg			☐	☐
1.10	Single leg hops straight on, left leg			☐	☐

Did you feel any pain and/ or difficulties while doing the following exercises? If you answer one of the following questions with 'yes', please add on which side the pain occurred.		**YES**	**NO**
2.1	Single leg stand (wobbling board), eyes open, right leg	☐	☐
2.2	Single leg stand (wobbling board), eyes open, left leg	☐	☐
2.3	Single leg stand (wobbling board), eyes closed, right leg	☐	☐
2.4	Single leg stand (wobbling board), eyes closed, left leg	☐	☐
2.5	Glute Bridge, right leg	☐	☐
2.6	Glute Bridge, left leg	☐	☐
2.7	Single leg squats, right leg	☐	☐
2.8	Single leg squats, left leg	☐	☐
2.9	Single leg squat jumps, right leg	☐	☐
2.10	Single leg squat jumps, left leg	☐	☐
2.11	Single leg hops, crossover, right leg	☐	☐
2.12	Single leg hops, crossover, left leg	☐	☐

D.1 Results of the Data Acquisition

Level I				Level II			
eyes open		eyes closed		eyes open		eyes closed	
right	left	right	left	right	left	right	left
60	60	10	60	60	60	42	23
60	60	60	49	60	60	60	3
60	60	10	34	60	60	8	17
60	60	40	11	60	60	5	4
60	60	35	4	60	60	5	42
60	60	10	7	60	60	9	15
60	60	7	30	60	60	7	9
60	60	0	15	60	60	60	29
60	60	55	52	60	60	18	15
60	60	4	4	60	60	7	5
60	60	60	59	60	60	15	42
60	60	11	13	60	35	4	7
60	60	60	60	60	60	60	9
60	60	15	25	60	60	6	14
60	60	60	3	60	60	60	12
60	60	20	15	60	60	6	10

Table D.1: Results of single leg stands.

Glute Bridges						Squats					
double		right		left		double		right		left	
detected	recorded	detected	recorded	detected	recorded	detected	recorded	detected	recorded	detected	recorded
36	36	36	36	42	42	30	31	49	50	37	37
21	22	24	21	21	22	24	24	19	19	16	16
17	17	20	20	24	24	16	16	18	17	17	17
31	30	-	-	13	14	23	24	-	-	19	19
28	29	50	50	53	55	26	26	58	57	63	62
24	23	9	9	11	11	25	26	23	23	12	12
26	26	22	22	19	18	20	21	29	27	26	26
36	37	39	39	35	35	28	29	40	40	33	33
21	22	41	41	29	29	32	33	45	46	46	46
27	27	18	19	17	17	21	23	21	21	24	23
17	18	50	52	-	-	28	29	41	41	-	-
29	29	15	12	21	21	31	32	14	14	22	22
35	33	11	12	18	15	34	33	-	-	-	-
21	22	24	25	22	22	23	24	46	48	30	31
25	26	18	18	13	13	23	24	25	25	27	28
21	21	9	10	11	12	24	24	19	19	25	26

Table D.2: Results of glute bridges and squats. Missing values are due to missing sensor data, as there were connection problems during the study.

Drop Jump				Squat Jump		Squat Jump, R		Squat Jump, L	
height		reaction time		height		height		height	
Force Plate	Sensor	Force Plate	Sensor	Force Plate	Sensor	Force Plate	Sensor	Force Plate	Sensor
0.33	0.36	0.49	0.45	0.34	0.37	0.15	0.17	0.13	0.17
0.37	0.39	0.36	0.25	0.33	0.37	0.16	0.22	0.15	0.20
0.33	0.34	0.45	--	0.34	0.37	0.18	0.20	0.18	0.19
0.23	0.24	0.29	0.21	0.18	0.22	0.08	0.10	0.07	0.09
0.20	0.19	0.35	0.26	0.19	0.23	0.10	0.13	0.08	0.10
0.17	0.17	0.33	0.19	0.19	0.24	0.06	0.10	0.04	0.08
0.29	0.29	0.33	--	0.26	0.20	0.13	no data	0.15	0.09
0.29	--	0.64	--	0.25	0.18	0.11	no data	0.15	0.12
0.30	0.29	0.38	0.30	0.24	0.19	0.13	no data	0.15	0.15
0.24	0.23	0.47	0.16	0.23	0.28	0.15	0.18	0.10	0.13
0.23	0.27	1.07	--	0.25	0.27	0.15	0.16	0.12	0.14
0.27	0.28	0.51	0.40	0.27	0.29	0.17	0.21	0.12	0.13
0.23	0.24	0.30	0.28	0.16	0.19	0.06	0.10	0.06	0.10
0.23	0.24	0.21	--	0.15	0.19	0.06	0.10	0.06	0.10
0.17	0.18	0.60	0.17	0.14	0.19	0.07	0.10	0.07	0.08
0.27	0.29	0.32	--	0.24	0.28	0.11	0.14	0.11	0.18
0.27	0.28	0.53	0.51	0.22	0.26	0.13	0.16	0.11	0.15
0.25	0.27	0.38	0.26	0.20	0.24	0.13	--	0.12	--
0.23	0.27	0.44	--	0.24	0.28	0.16	0.20	0.14	--
0.27	0.29	0.32	0.19	0.23	0.28	0.15	0.17	0.14	0.19
0.29	0.29	0.32	0.22	0.23	0.28	0.13	--	0.15	0.19
0.25	--	0.38	0.28	0.20	0.24	0.15	0.18	0.13	0.13
0.29	0.17	0.47	--	0.21	0.24	0.13	0.15	0.12	0.14
0.28	--	0.74	--	0.16	0.20	0.13	0.15	0.13	0.16
0.33	0.37	0.39	0.38	0.30	0.26	0.17	--	0.18	0.16
0.33	0.37	0.42	0.29	0.27	--	0.18	0.18	no data	0.17
0.34	0.37	0.51	--	0.27	0.32	no data	0.18	no data	0.22
0.21	0.21	0.55	0.48	0.17	0.20	0.08	0.09	0.07	0.09
0.19	0.21	0.31	0.19	0.16	0.20	0.06	0.08	0.06	0.08
0.18	0.20	0.21	0.18	0.16	0.18	0.07	0.10	0.08	0.08
0.37	0.37	0.58	0.16	0.35	--	0.20	0.24	0.19	no data
0.36	0.39	0.35	0.29	0.35	--	0.18	--	0.22	no data
0.38	0.36	0.61	0.59	0.32	0.16	0.18	0.23	0.18	no data
0.34	0.32	0.41	0.33	0.28	0.36	0.15	0.13	0.17	0.17
0.33	0.32	0.44	0.38	0.28	0.25	0.13	--	0.15	0.15
0.33	0.19	0.29	0.20	0.28	0.26	0.12	--	0.15	0.18
0.18	0.19	0.34	0.21	0.15	0.19	0.09	0.11	0.09	0.13
0.19	0.19	0.35	0.29	0.14	0.18	0.09	0.11	0.08	0.10
0.15	0.16	0.51	0.42	0.13	0.19	0.09	0.12	0.08	0.11
0.28	0.29	0.28	--	0.26	0.25	0.09	0.12	0.08	0.14
0.28	0.26	0.32	0.30	0.24	0.27	0.10	0.12	0.08	0.10
0.29	0.31	0.42	0.36	0.24	0.26	0.10	0.13	0.10	0.13
0.24	0.25	0.48	0.41	0.22	0.25	0.13	0.16	0.08	0.10
0.23	0.23	0.57	0.61	0.23	0.26	0.10	0.13	0.06	0.09
0.24	0.26	0.38	0.22	0.20	0.25	0.10	0.12	0.07	0.09
0.30	--	0.24	--	0.32	0.34	0.13	0.07	0.20	0.22
0.29	0.29	0.69	0.16	0.34	--	0.13	0.17	0.18	0.18
0.29	0.31	0.31	0.26	0.33	--	0.15	0.17	0.20	0.18

Figure D.1: Results of jump heights of 16 test subject with three trials per jump exercise. „No data“-cells are due to hardware connection problems. Missing values mark the jumps which were not or wrongly detected by the algorithm including for example detected landings but wrongly detected take-offs and the other way round.

Level I				Level II			
right		left		right		left	
detected	recorded	detected	recorded	detected	recorded	detected	recorded
6	6	7	7	8	8	7	7
12	11	12	11	14	14	-	-
9	10	9	9	-	-	12	12
8	8	10	10	8	9	10	10
12	13	13	12	10	10	12	11
10	10	9	9	11	11	10	10
8	8	-	-	7	7	-	-
14	15	16	15	11	11	12	12
8	9	9	9	7	9	8	8
10	10	9	10	12	12	11	11
9	9	8	7	12	13	-	-
3	7	9	9	8	8	8	8
10	10	12	12	15	15	14	14
10	10	10	11	11	12	14	14
10	10	9	10	11	11	12	12
8	9	8	8	10	11	11	10

Table D.3: Results of single leg hops. Missing values are due to hardware connection problems.

D.2 Questionnaire for the Expert Labeling

Assessment of the anatomical leg axis position. Based on photo of statical trial.

	genu valgum	genu varum	physiologically normal
test person standing			

Assessment of exercises. Based on videos. Three trials per video and exercise, please rate as overall impression of all three trials.

		Movement at the knee, „give way“, leg axis before take-off/ during push-off				
		medial		neutral	lateral	
		strong	slightly		slightly	strong
Drop Jump	right left					
Squat Jump	right left					
Squat Jump, R	right					
Squat Jump, L	left					

		Movement at the knee, „give way“, leg axis at landing/ after touchdown				
		medial		neutral	lateral	
		strong	slightly		slightly	strong
Drop Jump	right left					
Squat Jump	right left					
Squat Jump, R	right					
Squat Jump, L	left					

	Evaluation of the jump		Comments
	stable	not stable	
Drop Jump			
Squat Jump			
Squat Jump R			
Squat Jump L			

Curriculum Vitae

Personal Data

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Academic Education

since 10/2015	**Master of Science**, *FAU Erlangen-Nürnberg*, Erlangen, *Medical Engineering*. Master Thesis: Development of Algorithms for Computing Knee Stability Parameters Using a Sensor Equipped Knee Sleeve
10/2011 – 03/2015	**Bachelor of Science**, *Universität zu Lübeck*, Lübeck, *Medical Engineering*. Bachelor Thesis: Interaction between Ultrasonic Dissector Sonotrodes and Biological Tissue: Influences on Control Signal Properties
09/2008 – 06/2011	**Abitur**, *Wirtschaftsgymnasium*, Bad Mergentheim.

Internships and Student Trainee Activites

05/2017 – 12/2017	**Internship and Student Trainee**, *adidas AG*, Berlin/ Herzogenaurach, Project in cooperation with Otto Bock HealthCare: Sensor Equipped Knee Sleeve for Knee Injury Prevention.
11/2016 – 03/2017	**Student Trainee**, *Siemens Healthineers*, Erlangen.
07/2016 – 10/2016	**Scientific Internship**, *Orthopaedic Department and Völk Orthopädie*, Waldkrankenhaus, Erlangen.
10/2014 – 03/2015	**Internship and Bachelor Thesis**, *Söring*, Quickborn, “Interaction between ultrasonic dissector sonotrodes and biological tissue: Influences on control signal properties”.
07/2013 – 08/2013	**Internship**, *Labor für Biomechanik (UKSH)*, Lübeck, Determination of Initial Ground Contact During a Gait Cycle.

Additional Skills

Languages	○ German, first language ○ English, fluently ○ French, basics
Software	Microsoft Office, Matlab, Assembler (Basics), Java, C++

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