ETH Zurich
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Biomechanical Analysis of Selected Risk and Protective Factors for an Anterior Cruciate Ligament (Re-) Rupture during a Training with the ExerCube

Master Thesis

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Submitted by:
Michelle C. Haas

Supervisor:
Dr. Eveline Graf
Institute of Physiotherapy
Zurich University of Applied Sciences

Tutor:
Prof. Dr. Jörg Goldhahn
Institute of Translational Science
ETH Zurich

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Abstract

Movement patterns are altered after an anterior cruciate ligament reconstruction and rehabilitation, which could increase the risk for a second rupture. Therefore, rehabilitation needs to be improved. The use of exergaming and virtual reality has shown promising results in the rehabilitation of chronic disease patients, but not yet with patients after musculoskeletal injuries. The aim of this thesis was to investigate the biomechanical movement quality and the potential risk of an anterior cruciate ligament (re-) rupture during a training with the ExerCube, an exergaming device. Biomechanical movement patterns of female healthy athletes (n = 7) of five different type of sports were investigated. Measured biomechanical risk factors during jumps, squats, left, and right lunges were knee flexion angle (fraction between 10° and 30°) and knee adduction angle, while the investigated biomechanical protective factor was the hip flexion angle. Additionally, knee extensor and flexor strength were measured with isokinetic dynamometry. Participants showed low knee extensor strength and normal knee flexor strength. Both risk factors were present in all four exercises, even though to a different extent, whereas the protective factor was found only during the squat and the jump or lunge of some participants. Strain on the anterior cruciate ligament during the squat and lunge is controllable, but during the jump explosive movements create a high amount of loading. It can therefore be concluded that the squat and lunge can be performed during later stages of rehabilitation, but it is not recommended to perform a jump in the ExerCube training environment.

Abbreviations

ACL	Anterior Cruciate Ligament
ACLR	Anterior Cruciate Ligament Reconstruction
HF	Heart Frequency
H/Q	Hamstrings-to-Quadriceps
IR	Incidence Rate
PTS	Posterior Tibial Slope
RCT’s	Randomized Controlled Trials
REDCap	Research Electronic Data Capture
ROM	Range of Motion
VR	Virtual Reality
VRR	Virtual Reality Rehabilitation

1. Introduction

1.1 Anterior Cruciate Ligament

1.1.1 Anatomy

Consisting of bony structures, ligaments, cartilage and bursae, the hinge joint of the knee is a complex structure of the human body. It connects the body's two largest lever arms, the tibia and the femur (Figure 1). The range of motion (ROM) differs greatly between the six different degrees of freedom, which are allowed by the femorotibial and the patellofemoral joint. In the sagittal plane the ROM through flexion and extension is very high, whereas ROM through external and internal rotation in the transverse plane as well as varus and valgus stress in the frontal plane, is much more limited. The two bony articulations of the knee have different tasks. While the articulation between the femur and tibia is responsible for weight bearing, the articulation between the patella and the femur is responsible for the force transfer from the quadriceps femoris muscle over the knee with the least amount of friction possible. In addition to the, in articular cartilage covered, femoral and tibial condyle, the medial and lateral menisci, located between the two condyles, provide a frictionless surface and act as shock absorbers. Synovial fluid, coming from the four bursae in the knee, helps to reduce friction between adjacent moving structures as well (Abulhasan & Grey, 2017).

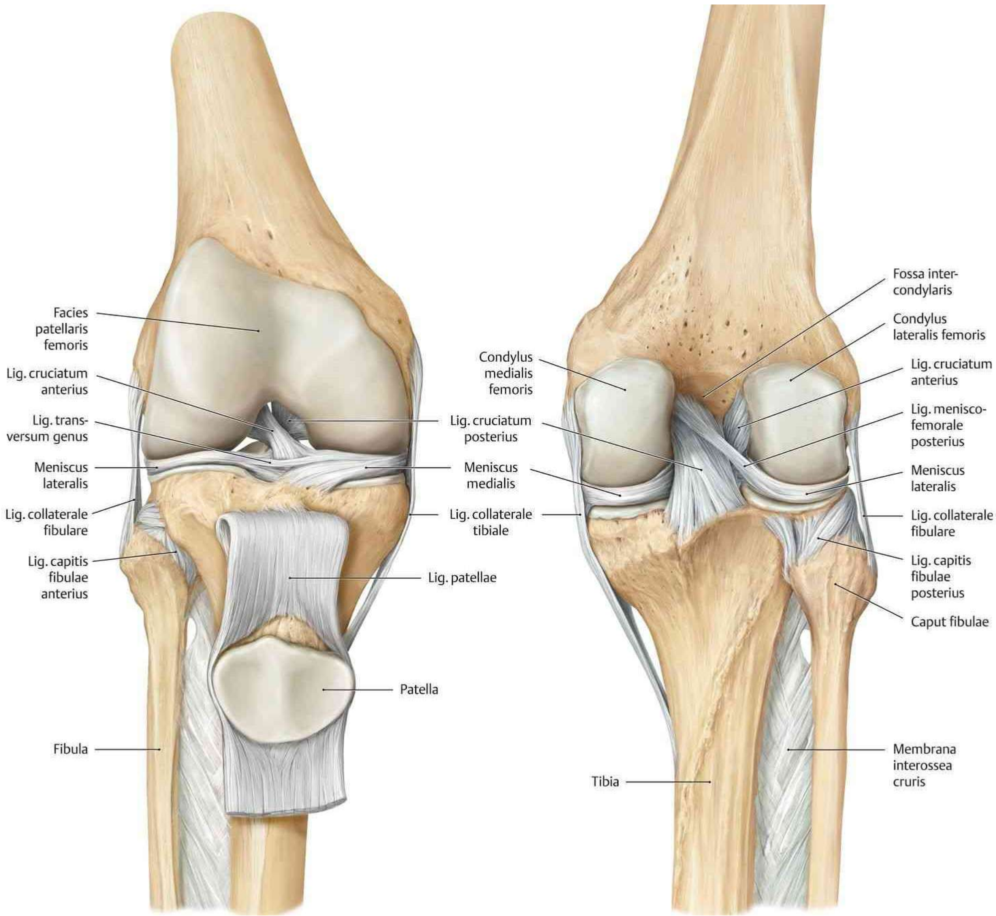

Figure 1: Anatomy of the knee joint from the front view (left) and the back view (right). (Schünke, 2018)

The knee joint is primarily stabilized by four different ligaments. The anterior cruciate ligament (ACL), the posterior cruciate ligament, the lateral collateral ligament, and the medial collateral ligament. They prevent excessive movements of the tibia relative to the femur in anterior and posterior direction as well as varus and valgus movements of the knee (Abulhasan & Grey, 2017). A valgus movement creates a compressive load on the lateral part of the knee joint whereas a varus movement creates a compressive load on the medial part of the knee joint (Koga et al., 2010). About 85% of the knee's stability can be attributed to the ACL and its main function of preventing anterior as well as rotational movements of the tibia relative to the femur (Abulhasan & Grey, 2017). The ACL consists of two bundles: the anteromedial bundle, strained when the knee is flexed, and the posterolateral bundle, strained when the knee is extended (Petersen & Zantop, 2007).

Secondary stabilisers are the muscles which surround the knee joint. Even though they primarily ensure movement along the six degrees of freedom of the knee joint, they play an important role in knee proprioception through interaction with the neuromuscular system. While the rectus femoris, the vastus lateralis, vastus medialis, and vastus intermedius of the quadriceps muscles ensure knee extension, the biceps femoris, semimembranosus, and semitendinosus of the hamstring muscles ensure knee flexion. Additionally, several other muscles of the thigh and shank aid in flexion and rotation of the knee (Abulhasan & Grey, 2017).

1.1.2 Epidemiology

In an epidemiologic study from the United States of America with data from 1988 - 2004 for collegiate athletes of 15 different sports, in more than 50% of all injuries the lower extremities were affected. Although ligamentous injuries to the ankle were more common (14.8 - 26% of all injuries), injuries to the ACL (3% of all injuries) and concussions (5 - 18% of all injuries) were more severe and lead to time loss of more than ten days. Additionally, the injury rate of ACL injuries and concussions increased over the investigated time period, whereas the number of ankle sprains remained on the same level (Hootman, Dick, & Agel, 2007).

Even though all four ligaments in the knee joint can rupture, the rupture of the ACL is the most common. In Scandinavia, continental Europe, New Zealand and the United States, the annual incidence rate (IR) of ACL injury sustained during sports is 0.03 - 0.04%, which equals 30 - 40 ACL injuries per 100'000 people. Among professional athletes the IRs are substantially higher with a range from 0.15 - 3.67% depending on type of sport and country (Moses, Orchard, & Orchard, 2012; Pasanen et al., 2008). In the United States, high IRs have been reported for football, lacrosse, gymnastics, basketball and soccer in high school, college or amateur athletes (Gans, Retzky, Jones, & Tanaka, 2018; Gornitzky et al., 2016; Montalvo et al., 2019). In Switzerland injuries are registered and classified through accident statistics. The latest publication reviewing data from 2013 - 2017 registered 1.07% of all accidents as dislocations, sprain, and strain (including ligamentous injuries) of the knee (SSUV, 2019).

1.1.3 Injury Mechanism

ACL injuries occur either without contact or with contact. Around 70% of all injuries are noncontact injuries, the remaining 30% are contact injuries (Sutton & Bullock, 2013). In Japanese high school basketball, handball and volleyball, non-contact injuries are more common than contact injuries, whereas in soccer no difference in the incidence of contact and non-contact injuries could be found. In the same study population, female basketball and soccer players had a significantly higher number of cutting- and stopping-injuries while in handball and volleyball players, a significantly higher number of landing-related injuries were registered (Takahashi, Nagano, Ito, Kido, & Okuwaki, 2019).

Most noncontact injuries occur when an athlete decelerates and suddenly changes direction during weight-bearing activities (Sutton & Bullock, 2013). A typical example of a noncontact injury is when an athlete lands from a jump with an extended and internally rotated hip, a knee near full extension and at a valgus position, the tibia internally rotated, and a planted foot (Kaeding, Léger-St-Jean, & Magnussen, 2017). The injury mechanism for noncontact ACL injury is highly debated and several theories, obtained through different methods such as video analysis or cadaver testing, have been proposed. In 2010, Koga et al. introduced an ACL injury pattern which consists of three main steps. First, knee valgus load is applied which leads to lateral compression and therefore a strained medial collateral ligament. Second, the lateral compression force and the anterior force vector, caused by quadriceps contraction, lead to a posterior shift of the lateral femoral condyle and both an anterior shift and internal rotation of the tibia. This initiates the rupture of the ACL. Third, after the ACL rupture, the primary restraint to tibial anterior translation is inexistent. This results in a posterior displacement of the femoral condyle and an external rotation of the tibia (Koga et al., 2010). This theory is supported by various other proposed potential risk factors to ACL injury. Boden et al. (2010) proposed that several forces contribute to a noncontact ACL injury. The primary contributor is likely to be an impulsive external axial force. In certain positions of the body at initial ground contact, such as a flat foot and an increased hip flexion angle, the dampening capabilities of the leg are reduced which leads to a higher risk of injury. Because of decreased stability of the knee when in a valgus position, the threshold for a noncontact ACL injury may be reduced. Quadriceps contraction increases the compressive forces on the knee which reduces the threshold for an injury as well (Boden, Sheehan, Torg, & Hewett, 2010). Another potential injury mechanism was introduced by Demorat et al. (2004) and is usually referred to as the quadriceps drawer mechanism (Grassi et al., 2020). It states that due to the patellar tendon angle, the quadriceps muscle generates anterior shear forces on the tibia which then results in an ACL rupture (Demorat, Weinhold, Blackburn, Chudik, & Garrett, 2004). Fung and Zhang (2003) found that the strain on the ACL is increased when the tibia rotates externally and is abducted at moderate knee flexion (Fung & Zhang, 2003). When cadaver knees were loaded with compression forces, the femur displaced posterior relative to the tibia while pre-failure of the ACL the tibia rotated internally and post-failure the tibia rotated externally (Meyer & Haut, 2008).

1.1.4 Risk Factors

There are extrinsic and intrinsic risk factors for an ACL rupture. Since female athletes have a higher risk of an ACL injury, for example in basketball and soccer where the injury rate for females is three times higher than for males, Sutton and Bullock (2013) reviewed the differences of risk factors between the two genders. Extrinsic risk factors such as floor surface, climate, or shoe sole are non-sex specific. But intrinsic risk factors differ greatly between men and women. Women have a higher quadriceps angle, which means the quadriceps pulls more at the knee in a lateral direction. This may leave the ACL at a more vulnerable position to rupture. Even though there are differences in intercondylar notch widths and shapes between individuals, up until now no conclusive evidence, regarding which shape and width leads to the highest risk for an ACL rupture, exists. The size of the ACL is smaller in females than in males, when standardised for body weight. But it is unclear whether this leads to an altered risk for ACL injury. The size of the posterior tibial slope (PTS) received some interest lately, because a greater PTS leads to a more anterior position of the tibia in relation to the femur during quadriceps contraction. This in turn leads to a possible increased strain on the ACL. Up to date, no significant differences could be found between men and women on this subject (Renstrom et al., 2008; Sutton & Bullock, 2013).

Hormonal levels are very different between men and women. Since on ACL fibroblasts, estrogen receptors are present, hormones may have an influence on collagen synthesis, knee laxity, and the strength of supporting muscles around the knee (Sutton & Bullock, 2013). During the ovulatory phase of the cycle, the concentrations of estrogen and relaxin, which both affect the tensile properties of the ligaments, peak. While estrogen decreases ligament strength, relaxin decreases soft tissue tension (Hewett, Myer, & Ford, 2006). Through relaxin-induced collagen degeneration progesterone decreases ACL laxity (Konopka, Hsue, & Dragoo, 2019). The muscle is directly affected by estrogen peaks and may therefore influence the neuromuscular control of joints. When taking oral contraception, large fluctuations of hormonal levels, especially estrogen peaks, are diminished. This may block the naturally occurring effects of hormones on knee stability (Hewett et al., 2006). A systematic review of Konopka et al. (2019) concluded that the use of oral contraceptives may act to decrease the rate of ACL injuries and may act to decrease anterior tibial translation (Konopka et al., 2019). Although there is a tendency towards an increased risk for an ACL injury in the early and late follicular phases, the currently available evidence on hormonal influence is still inconclusive (Sutton & Bullock, 2013). According to Hewett et al. (2006) these inconclusive results could be due to the varying influence of estrogen and relaxin on ligament collagen which could lead to a lack of control of this variable in research. The influence of oral contraceptives is still highly controversially discussed as well (Hewett et al., 2006; Renstrom et al., 2008).

Even though both sexes have an equal risk of re-rupturing the reconstructed knee, females are at greater risk to rupture the contralateral ACL (Sutton & Bullock, 2013). Through analysis using a geographic database, the incidence of second ACL tears and associated risk factors were calculated by Schilaty et al. (2017). A total of 13.8% of all injured individuals had a second ACL injury of which 46.1% had a graft rupture, 50.4% teared the contralateral ACL, and 3.5% ruptured the contralateral graft. Of all second ACL injuries 74.5% occurred via noncontact mechanism. Significant predictive values for a second injury could be established for females aged 17 to 25 years for a re-rupture and nonoperative treatment for contralateral injury (Schilaty et al., 2017).

There are two main muscle groups which are predominantly responsible for moving the knee, but also act as stabilising agents. The quadriceps muscles induce knee extension, whereas the hamstring muscle group induces knee flexion (Abulhasan & Grey, 2017). Quadriceps muscle force leads to increased forces of the ACL, while hamstring muscle force reduces loads in the ACL through posterior shear forces which stabilize the knee (Shimokochi & Shultz, 2008). Because the quadriceps-to-hamstrings mass ratio is higher in females than in males (Sutton & Bullock, 2013), as well as their hamstrings-to-quadriceps peak torque ratio (Hewett et al., 2006), women have a higher risk of injury. When tilting the trunk forward, for example during landing, hamstring and gluteus maximus forces are increased. This results in an increase of the hip extension moment, but a decrease of the knee extension and knee valgus moment, which might all be associated with decreased loading of the ACL (Hughes, 2014). Escamilla et al. (2012) found similar results, stating that a forward trunk tilt of 30° to 40° results in more hamstring activation which unloads the ACL (Escamilla, Macleod, Wilk, Paulos, & Andrews, 2012). A correlation between the forward inclination of the trunk and knee flexion angle exists (Nagano, Ida, Akai, & Fukubayashi, 2011).

1.1.5 Treatment and Rehabilitation of an ACL Rupture

Following an injury, patients usually undergo physical therapy for a few weeks before deciding on conservative treatment or surgery (Eitzen, Moksnes, Snyder-Mackler, & Risberg, 2010). According to Krause et al. (2018) conservative treatment is more suitable for patients without a high activity level or associated lesions. In their view, the fact that conservative treatment is of equal value to surgery cannot be confirmed. Even though functional improvement following surgery seems to be greater than after conservative treatment, it is dependent on the qualities of the surgeon (Krause et al., 2018). Other authors also state, that athletes who want to return to a sport which requires the use of the ACL, need to do the reconstruction (Cheatham & Johnson, 2010). This fact is supported by a majority of 64% who chose surgery (mean age 24.5 years, 81% activity level I) in the study of Eitzen et al. (2010). Activity level I means that a sports activity requiring jumping, cutting, and pivoting movements or an occupational activity with comparable demands is performed (Hefti, Müller, Jakob, & Stäubli, 1993).

Rehabilitation after ACL reconstruction (ACLR) is not standardized and differs between surgeons, physical therapists and other rehabilitation experts. A recently published systematic review of clinical practice guidelines by Andrade et al. (2020) led to several recommendations regarding rehabilitation. Immediate mobilisation, strength and neuromuscular training is encouraged as well as early full weight bearing and open kinetic chain exercises. Additionally, to personal preference of the rehabilitation specialist, closed kinetic chain exercises, cryotherapy and electrical stimulation of the muscles can be added to the rehabilitation program (Andrade, Pereira, van Cingel, Staal, & Espregueira-Mendes, 2020). Several authors proposed the integration of reactive movements and other sensory-visual-motor control factors into the rehabilitation process after ACLR (Buckthorpe, 2019; Gokeler, Neuhaus, Benjaminse, Grooms, & Baumeister, 2019). The functional rehabilitation after surgery is usually carried out by a physical therapist who ensures treatment quality and is the only source of feedback. Due to often repetitive movements and exercises the patient might encounter motivational problems (Tannous et al., 2016). Motivation is an important factor for good adherence which in turn leads to a better outcome of rehabilitation (Howard, 2017). Current rehabilitation protocols do not lead to optimal outcomes because after ACLR, patients exhibit altered movement patterns (Buckthorpe, 2019; Hart et al., 2016; Mazaheri et al., 2017; Stone, Roper, Herman, & Hass, 2018) and altered posture (Mohammadi-Rad et al., 2016). Additionally, altered movement quality can lead to an elevated risk for a secondary ACL injury (Buckthorpe, 2019). Usually, strength measurements of the hamstrings and quadriceps muscles are made after ACL rehabilitation in order to determine whether athletes are ready to return to sports. These measurements are most commonly made with an isokinetic dynamometer (Andrade Mdos et al., 2012; Undheim et al., 2015).

1.2 Virtual Reality and Exergaming in General

1.2.1 Virtual Reality

A virtual reality (VR) environment should include the three I's: immersion, interaction and imagination (Burdea & Coiffet, 2003). This means that the user should be brought to a virtual environment in which he feels immersed and can respond to in real time. According to Tieri et al. (2018) *"a fully immersive VR allows a natural interaction with the surrounding environment by using the entire body of the user that becomes, this way, an active part of the 3D environment*". With VR it becomes possible to realistically react to a certain stimuli which can be of advantage in future motor rehabilitation programs (Tieri, Morone, Paolucci, & Iosa, 2018).

1.2.2 Exergaming

Exergaming is defined as *"an experimental activity in which playing exergames or any videogames that requires physical exertion or movements that are more than sedentary activities and also include strength, balance, and flexibility activities"* (Oh & Yang, 2010). Commercial exergaming systems exist since the 1980s. Back then exercise bikes or foot operated pads acted as controllers and ensured the interaction of the system and the performing human. Around the turn of the millennium the first motion sensor systems appeared on the market (Sinclair, Hingston, & Masek, 2007). For several exergames, like the Nintendo Wii, PlayStation Move or Xbox Kinect, new home video consoles are still released (Kooiman & Sheehan, 2015). The popularity of VR leads to its use in the field of exergaming (Donath, Rössler, & Faude, 2016; Farrow, Lutteroth, Rouse, & Bilzon, 2019).

1.2.3 Dual Task during Exergaming

Since an individual playing an exergame has to perform a cognitive and a motor task simultaneously, it can be defined as a dual task performance (Fraser & Li, 2012). This dual task demand of exergames has advantages since a short review by Costa et al. (2019) found that it could improve motor as well as cognitive function in different study populations. In children with cerebral palsy, exergaming led to increased levels of attention and concentration and additionally improved upper limb motor function or manual force. Studies with institutionalized elderly people could show that after a single session the semantic memory and executive function was improved and after 12 - 16 sessions short term memory and mobility was superior than before. Motor function, balance, and cognitive functions were improved after exergaming in stroke survivors. People affected by Parkinson's disease could improve balance and other clinical parameters after exergaming. Overall neurobiological effects of exergaming are the same as with traditional exercise if the participant moves in the same way. Additionally, the cognitive work during exergaming could increase neuroplasticity which has the potential to increase the problem-solving ability and sensorimotor integration (Costa et al., 2019).

When performing a dual task, the cognitive resource theory can be applied. It states that there is a limited amount of renewable cognitive resources, which are needed for attention and information processing. In order to perform a dual task, a trade-off must be made to manage on these limited resources. This trade-off depends on the motor activity with which the cognitive task is tested. In a study using free word recall and outdoor running, Epling et al. (2016) found that participants preserved the motor task performance more than the cognitive task when tested simultaneously (Epling, Blakely, Russell, & Helton, 2016). Contrary conclusions were made by Kang et al. (2018). They stated that the performance during the cognitive task and the dual task was reduced when the cognitive load was higher and that the cognitive task received more attentional resources than the motor task (Kang, Shin, Yun, Park, & Park, 2018).

Other studies compared the performance of a single motor task with the performance of a dual task under laboratory conditions to determine the amount of attentional resources needed in order to sustain the same level of performance. Dai et al. (2018) assessed jump performance as motor task with simultaneous backward counting as cognitive task. In the dual task condition, the performance, measured by jump height, decreased. Investigation of landing mechanics led to the conclusion that the cognitive task had an impact on pre-landing biomechanics and preparatory neural mechanisms since the knee flexion angles at initial contact decreased significantly when the cognitive task was performed (Dai et al., 2018). Demirakca et al. (2016) found that due to coactivation, brain plasticity can be induced through an integrated multimodal training that combines motor and cognitive aspects (Demirakca, Cardinale, Dehn, Ruf, & Ende, 2016). This suggests that dual task conditions enhance brain connectivity.

Since more research on dual task is made under laboratory conditions than in the field, it is difficult to establish which performance will receive more resources when training with an exergaming device. Additionally, few studies investigating dual task performance after musculoskeletal injuries exist.

1.3 Virtual Reality and Exergaming in Rehabilitation

1.3.1 Home Based Rehabilitation

Several therapists are needed to ensure a qualitatively high rehabilitation, which leads to high costs. Therefore, home based rehabilitation was established as a new research field with the aim to change this situation. Six randomized controlled trials (RCT's) comparing home-based and centre-based (either group or individual) physical therapy after ACLR were analysed in two systematic reviews by Wright et al. (2008) and Kruse et al. (2012). In all of the RCT's except one, no significant differences could be found in the evaluation after the treatment period. The RCT's could all have performance bias since different physical therapists supervised the home-based and the centre-based groups (Kruse, Gray, & Wright, 2012; Wright et al., 2008). Therefore, better RCT's are needed to conclude if home-based rehabilitation provides an advantage. Because in the RCT's no differences could be found, it is already established that it does not provide a disadvantage.

1.3.2 Virtual Reality in Rehabilitation

VR is a new development in rehabilitation. Simple computer monitors, surround-screen displays, or even head-mounted displays are available tools for virtual reality rehabilitation (VRR). Movement in VRR can be controlled either by mouse, joystick, keyboard, sensors, or even treadmills (Holden, 2005; Howard, 2017). Three concepts are especially important in rehabilitation: repetition, feedback and motivation. VR is able to provide all three elements to the patient. Most notably, feedback can be improved in a VR environment. Repetition alone cannot induce cortical neuroplasticity when motor learning, but the learning rate can be improved with feedback after each repetition. Feedback can be given immediately since the system is programmed to detect and correct errors rapidly (Holden, 2005) and immediate feedback enhances learning (McConville, 2012). The feedback provided by VR is a new form of immersive biofeedback (Giggins, Persson, & Caulfield, 2013), which is delivered via graphical or audio-visual cues or both (McConville, 2012). With feedback, patients can improve accuracy, engage more, and the ongoing contact with a professional to monitor movement quality is reduced (Giggins et al., 2013). An important addition in VRR is the use of a virtual teacher, who can repeat movements as often as needed with the same accuracy. Through observation, mirror neurons, which directly influence the primary motor cortex, are activated and enhance learning (Holden, 2005). In addition to the aforementioned advantages of VR in rehabilitation, Barzilay and Wolf (2013) state that VRR has the advantage to collect quantitative data of the training process (Barzilay & Wolf, 2013).

In a meta-analysis, Howard (2017) found that overall, VRR programs are more effective tools than traditional rehabilitation programs, especially in strength development. Although, some results of this meta-analysis should be considered with caution because the effects in gait and motor control were only marginally significant and had variation. Only strength results had a large significant effect. Since VR can provide different stimuli, excitement is added, as well as a motivating challenge due to the gaming elements. Additionally, rehabilitation exercises are more realistic and therefore activate more realistic motor and neural pathways, which can be an advantage when performing the real-life task after rehabilitation. However, currently it is not known which mediating mechanisms lead to improved outcomes after VRR (Howard, 2017).

Exergaming acts as an example for VR in rehabilitation and can improve exercise execution, body equilibrium, joint flexibility and muscle strength (Tannous et al., 2016).

1.3.3 Dual Task during Rehabilitation

When adding a cognitive load to the rehabilitation program, the dual task performance increases (Howard, 2017). A certain degree of cognitive challenge can contribute to optimal physical performance, but if the challenge exceeds the processing capacity of the brain, performance decreases. The relationship between motor task and cognitive task performance is very complex. Depending on which type of cognitive challenge the participant is facing, the decrements may involve the motor or the cognitive task. In a review, Burcal et al. (2019) investigated the effect of a dual task condition on movement patterns of injured individuals. Of the eight studies investigating ACL injury, 71% found at least one alteration in motor performance. In 75% of the studies a significant task or condition difference between single and dual task was found, whereas in 25% of the studies no differences were reported or assessed. These numbers show that the movement patterns are changed when facing an additional cognitive load to the physical load, even though at the moment no evidence regarding cognitive loading in rehabilitation for musculoskeletal injury exists (Burcal, Needle, Custer, & Rosen, 2019). Burcal et al. (2019) as well as Gokeler et al. (2019) have found that ACL-injured individuals rely more on visual input and cortical motor planning to control knee movements which leads to a competition of attentive resources in line with the cognitive resource theory. However, it remains still unclear whether the trade-offs involve the cognitive or the motor task (Burcal et al., 2019).

After investigating motor learning principles to optimize performance and reduce the risk of a second ACL injury, Gokeler et al. (2019) proposed four key concepts that may enhance rehabilitation.

1. Attentive demands could be reduced with an external focus of attention. This external focus can be achieved by shifting the patient's consciousness to the effects of the motion on the environment. Through increased intracortical inhibition, the attentional demands are then reduced.
2. Implicit learning, allowing the patient to 'feel' a movement, would promote automated movements. By using limited visual information through implicit learning, the anticipatory skills of an athlete can be improved.
3. In contrast to providing athletes with only one movement strategy or exercise for a certain movement pattern, with differential learning rehabilitating athletes would find their individual, optimal movement strategy.

4. Self-controlled learning positively influences motor learning due to positive reinforcement which is provided through intrinsic motivation, interest, and enjoyment. Contextual interference, meaning *“the interference in performance and learning that arises from practicing one task in the context of other tasks”* (Gokeler et al., 2019), prepares athletes for their return to sports.

The authors conclude that, especially during the late stages of rehabilitation, reaction time, information processing, focus of attention, visual-motor control, and complex task-environment interactions should receive more attention (Gokeler et al., 2019).

Some of these motor learning principles could be applied during a training in the ExerCube. When assessing the cognitive load in respect to risk of an ACL rupture, a cognitive load may decrease the ability to reactively stiffen the knee joint, which can be a negative risk factor for ACL rupture (Kim et al., 2016).

1.4 The ExerCube

The ExerCube fitness game is an example for an immersive exergaming device with the use of VR (Figure 2). Research-based fitness concepts are combined with an attractive game design. It consists of three walls which surround the player and serve as projection screens and haptic interface for body interactions (Sphery, 2020a). Players wear trackers attached to their wrists and ankles (Appendix A), and an optional heart rate sensor, which act as controllers.

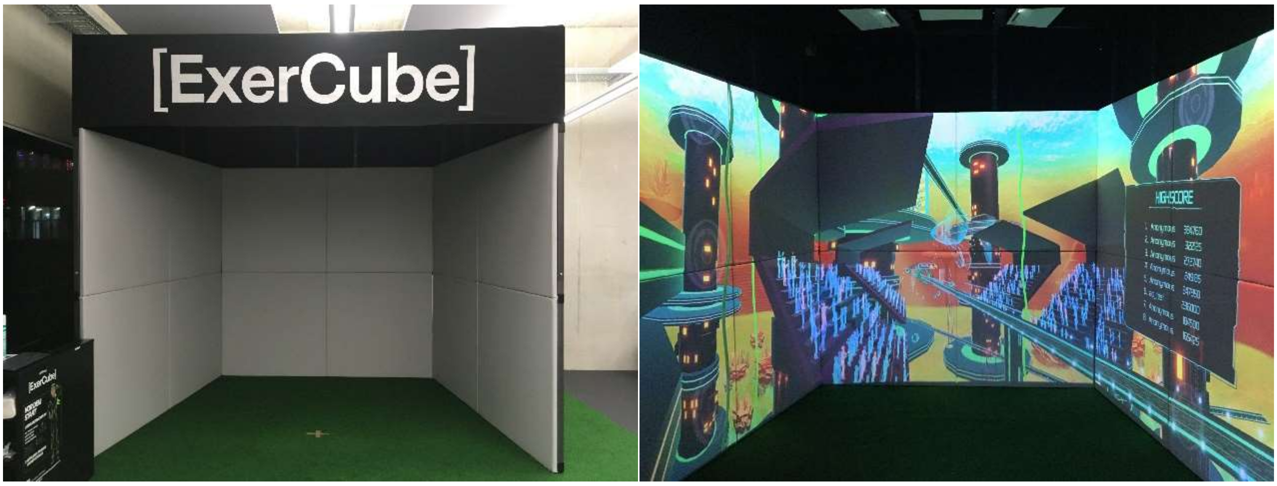

Figure 2: The ExerCube without running projectors (left side) and the ExerCube experience (right side) when the system is turned on (Reference: Own pictures).

After a warm-up phase, the adaptive program of the ExerCube trains at anaerobe to high intensity levels according to the player's individual motor-cognitive and motor-coordinative skills. There are five different levels. At each level additional exercises are introduced (Table 1).

Table 1: Exercises of the ExerCube at each level (Martin-Niedecken, Rogers, Vidal, Mekler, & Segura, 2019).

Level	Exercises
I	Low Touch Right or Left Touch Right or Left High Touch Right or Left
II	Punch Right Punch Left
III	(basic) Jump (Sumo-) Squat
IV	Lunge Right Lunge Left
V	Tripples Burpee

During all exercises, except the punches and the lunges, the player faces the front wall. All touches include shuffle steps to either the right or the left wall and a touch of the targets on the wall, which can be at three different heights. The punches are executed by the opposite hand requiring lateral rotation. Deep lunges are performed facing the edge of the ExerCube. During the tripples, small and fast steps are required to complete the exercise in time. For the burpee, first a basic jump is performed followed by a jump into the plank position with an optional push-up until the speaker of the game asks the player to get up. Detailed descriptions and figures of the different exercises can be found in appendix A. Feedback is provided via visual and auditory cues (Martin-Niedecken et al., 2019). When training with the ExerCube for the first time, one is easily overwhelmed by all the visual and auditory inputs. Another challenge is to understand what the correct movement of the extremities for each task has to be, so that the system recognises it and rewards points. With learning it gets easier to process all stimuli and move with the adequate quality and timing (Martin-Niedecken et al., 2019).

Previously, a study comparing the ExerCube training versus a training session with a personal trainer was conducted. Experiences of participants between the two conditions were compared in several aspects. Distinct differences were found in mental focus, perception of exertion, and execution in movements. ExerCube players' experience showed that the focus during a training session is completely on the game, whereas during a personal training session the mental focus was on the trainer or the own body. During the training with the ExerCube physical exertion was not noticed, but in personal training the participants noted the exertion. Movement quality was more uniform in the personal training condition. In the ExerCube, the movements depended more on environmental factors (Martin-Niedecken et al., 2019).

It is unknown whether a training session in the ExerCube is safe for patients after ACLR. Therefore, a biomechanical quality assessment of the movements during a training session in the ExerCube is needed to know if it is applicable for rehabilitation purposes. This is the aim of this master thesis. To the authors knowledge, no such quality assessment exists.

1.5 Research Question

1.5.1 Primary Research Question

Does the cognitive and physical challenge of the ExerCube training lead to a knee flexion angle between 10° and 30°, which is a biomechanical risk factor for an ACL (re-) rupture?

1.5.2 Secondary Research Questions

Does the cognitive and physical challenge of the ExerCube training lead to a valgus of the knee, which is a biomechanical risk factor for an ACL (re-) rupture?

Does a trunk inclination angle of 30° to 40°, which unloads the ACL, occur during a training with the ExerCube?

1.6 Hypotheses

1. The challenge of the ExerCube leads to knee flexion angles between 10° and 30° when training with the ExerCube.
2. The challenge of the ExerCube leads to valgus of the knee when training with the ExerCube.
3. A trunk inclination angle of 30° to 40° occurs when training with the ExerCube.

2. Materials and Methods

2.1 Participants

A total number of 14 female participants aged 18 - 32 years (Mean: 25.25 years, SD: 3.72 years) which play either basketball, handball, floorball, soccer or volleyball were recruited in and around the city of Winterthur through distribution of study information to sports clubs. Participants were regularly physically active in a competing sports team with at least two training sessions per week, each lasting at least one hour (Mean training hours per week: 4.58 hours, SD: 2.10 hours). Only healthy participants without any cardiovascular, pulmonary or musculoskeletal diseases were included. Additionally, sufficient German language skills were required. At the time of the two measurement sessions participants had to be within days 0 - 12 of their menstrual cycle (= follicular phase). Participants were excluded if they were pregnant or breastfeeding, a doctor prohibited high impact sports, they had any prior surgery to the lower limbs, they had a prior injury to the anterior cruciate ligament, or they were unable to give consent. After the pre-screening one participant dropped out due to an ACL injury and one participant dropped out after the first measurement session due to an ankle sprain during training.

The final study sample consisted of five volleyball players (42%), four soccer players (34%) and one player of each basketball (8%), floorball (8%), and handball (8%). Average height was 168.67 centimetres (SD: 4.54 centimetres) and average weight was 65.1 kilograms (SD: 5.25 kilograms). In all participants, the right leg was the dominant leg. Two third of the participants (n = 8) took hormonal contraception while one third (n = 4) did not. Only four participants had an injury during the past six months. These injuries were contusion of the carpal bones of the hand (n = 1), contusion of the right thumb saddle joint (n = 1), superior labrum anterior and posterior lesion of the left shoulder (n = 1), and left ocular contusion (n = 1). No participant did report any pain or injury of the lower extremities at the day of the measurements, nor did feel impaired by any prior injuries to the upper extremities when performing.

2.2 Procedure

When athletes were interested in participating, a pre-screening was made in order to determine whether inclusion and exclusion criteria are fulfilled. After passing the pre-screening, a detailed information about the study and its procedure was sent by e-mail (Appendix B). Participants were asked to read the information carefully, but not sign the informed consent document until the measurement session. Upcoming questions were answered either via phone, e-mail or personally at the measurement session. Two measurement sessions with three assessments were planned (Figure 3).

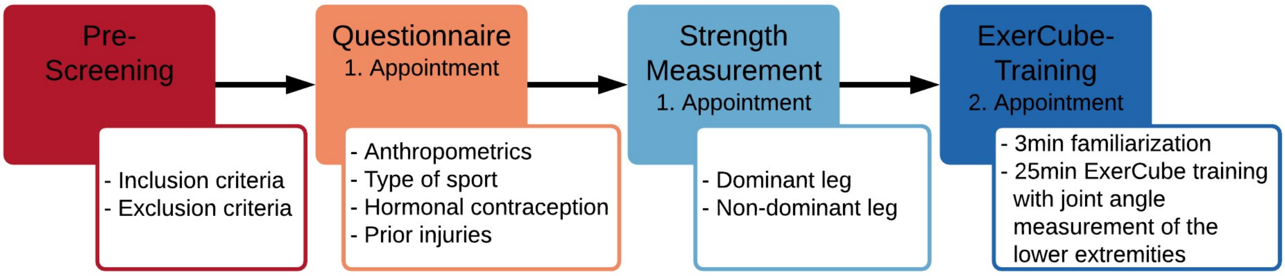

Figure 3: Overview of the different measurement sessions (Reference: Own illustration).

A clarification of responsibility was submitted to the ethics committee of the canton Zurich (BASEC-Nr. Req-2020-00820). After revision of the project, the ethics committee decided that the project does not fall under the human ordinance act and therefore no approval of the cantonal ethics committee is needed.

2.3 First Measurement Session: Strength Measurement and Questionnaire

Isokinetic dynamometry of knee flexion and knee extension was performed at the WIN4 Medbase in Winterthur with the HUMAC Norm (Model 502140, Computer Sports Medicine Inc., Stoughton USA) in a seated position. After arriving at the testing facility, all questions regarding the procedures of the study were answered and the informed consent document was signed by the participant and the investigator. Then, it was assessed whether they still met the selection criteria. Since strength measurements were adjusted to each individual's body weight, body weight was measured in sports gear but without shoes. Afterwards, participants performed a warm-up on a cycle ergometer for five minutes with a Watt performance of twice their body weight. During the warm-up, the questionnaire (Appendix C) involving questions regarding age, type of sports, training hours per week, dominant leg, hormonal contraception and prior injuries was answered by the participant and the testing procedure for knee flexor and knee extensor was explained thoroughly. The dominant leg was determined as the leg which is being used to kick a ball.

After sitting on the testing instrument, the backrest including lumbar cushion was adjusted, and the rotational axis of the dynamometer was aligned with the knee joint. It was assumed that the line passing transversely through the femoral condyle is the centre of rotation. To find the centre of rotation, the joint space of the knee was found through palpation of the fibula head. The lever arm was adjusted to each individual's lower leg length such that the pad was on the athlete's tibia just above the malleolus. Afterwards, the participant's position was secured through a seat belt, shoulder belts and a thigh stabilizer strap. The participants had to place the contralateral limb behind the stabilizer and put their hands on the corresponding rails. The ROM was set from 0°, which equals full extension, to 90°. Boundaries of this ROM were set by the program and mechanically with stops, which were placed according to each individual's ROM. The ROM was tested thoroughly such that the participant felt comfortable and a secure test was possible. The testing protocol occurred as follows, first for the dominant limb and then for the non-dominant limb:

1. 3 trial repetitions at 240°s^{-1} with submaximal effort (not included in the analysis)
2. 10 seconds break
3. 3 repetitions at 240°s^{-1} with maximal effort (not included in the analysis)
4. 60 seconds break
5. 3 trial repetitions at 60°s^{-1} with submaximal effort (not included in the analysis)
6. 10 seconds break
7. 3 repetitions at 60°s^{-1} with maximal effort
8. 60 seconds break

During the trial repetitions participants were asked to give 80% of their maximal effort. While participants were performing the three repetitions with maximal effort, they were encouraged verbally by the investigator. With the repetitions at 240°s^{-1} with maximal effort participants could get accustomed to the testing procedure. For the angular velocity of 60°s^{-1}, the peak force of the knee extensor and the knee flexor was used for analysis of leg differences and the hamstrings to quadriceps (H/Q) peak torque ratio was used for analysis of strength distribution between the knee flexor and extensor. The effect of gravity was not corrected.

Study data were collected and managed using REDCap (Research Electronic Data Capture), a web-based software platform designed to manage research study data, with a secure server hosted at Zurich University of Applied Sciences (Harris et al., 2019; Harris et al., 2009).

2.4 Second Measurement Session: ExerCube Training

Before the ExerCube training could start, at least 24 hours must have passed since the strength measurement to ensure proper recovery. Since participants had to be between days 0 and 12 of their menstrual cycle (= follicular phase), the two measurement sessions could not take place more than 12 days apart from each other. After arrival of the participant, a video including detailed information on how to perform the exercises in the ExerCube was shown (Sphery, 2020b). This video was shot and provided by Sphery Ltd., the manufacturer of the ExerCube. Then, the participant's height was measured. After the correct placement of the trackers on each wrist and each ankle, a familiarization session lasting three minutes and including a stepwise introduction of all the different exercises through tutorials, was performed. Since tutorials were only available in English, participants were asked to not hesitate to ask questions when they were having difficulties understanding the foreign language. In order to see the tutorial, the DualFlow program was chosen in workout mode. Workout mode meant that the exercises were chosen randomly. The aimed heart frequency (HF) was chosen as 80% of maximal HF. The maximal HF is automatically calculated by the program after insertion of information on the participant's age and weight. If any questions regarding the correct performance of any exercise came up, it was answered by the investigator. When performing, visual and acoustic feedback was automatically generated by the ExerCube program. Furthermore, motivational commands on how to perform each exercise correctly were presented verbally in English. As soon as the familiarization session was finished, the XSens MTw Awinda measuring system was put on. Each sensor and each strap was placed according to the instructions provided by the manufacturing company. Only lower body sensors (foot right and left, lower leg right and left, upper leg right and left, and pelvis) were applied. Figure 4 shows where all straps and sensors were placed in a participant. Detailed pictures of the MTw Awinda sensor placement can be found in appendix D.

Figure 4: Back view of the placement of the measuring system on a participant (Reference: Own picture).

Before the training and simultaneous measurement session could start, the system had to be calibrated. To achieve a good quality of the calibration the participant had to stand still for a few seconds and the room had to be clear of interfering objects. The participant’s height had to be provided to the program, so that the calculations (described in detail in 2.4.2) were more accurate.

As soon as the participant was ready to perform again, the 25-minute DualFlow workout in the competition mode with seed was started. A seed is a pre-defined order of exercises, so that each participant has the same order of exercises and only the pace at which they occur is adjusted. The chosen seed number “0508” consisted of a total of 651.1 ± 29.6 exercises, depending on the performance level. Half of the exercises had to be performed on the right side and the other half on the left side. The distribution of exercises in the chosen seed can be seen in appendix A.

A camera, recording with 60 frames per second, was placed behind the participant in the middle of the ExerCube room and approximately at the height of the participant’s knee joint. The video data was used to determine the start and end of each exercise.

2.4.1 XSens MTw Awinda

The XSens MTw Awinda (XSens Technologies, Enschede, Netherlands) is a system consisting of inertial magnetic units which are wirelessly connected to the computer program MVN Analyze. It is able to calculate joint angles based on position data from the sensors. Additionally, it can collect data about angular velocity, acceleration, earth magnetic field, and atmospheric pressure in 3D. Previously, it has been shown that XSens is a reliable tool to measure joint angles (Zhang, Novak, Brouwer, & Li, 2013). The XSens measuring system saves data at 60 Hertz.

2.4.2 Calculations

The MVN Analyze software accompanying the XSens MTw Awinda allows to export an mvnx-file containing information about position, velocity, angular velocity, acceleration, angular acceleration, centre of mass, time code, joint angle, motion tracker acceleration, motion tracker angular velocity, motion tracker orientation, and motion tracker magnetic field. Calculation of the joint angles by the MVN Analyze program occurs as follows.

After calibration the MVN Analyze sets the right heel of the participant as origin (0,0,0) of the global coordinate system. For each joint a local coordination system is defined with the centre of rotation as origin, X pointing forward, Y pointing upward from joint to joint, and Z pointing to the right. Each functional axis is described as the rotation around the two adjacent axes, for example for the knee joint, of the lower leg with respect to the upper leg. Flexion/extension occurs around the Z-axis, abduction/adduction around the X-axis, and endo/exo rotation around the Y-axis. The MVN Analyze calculates joint angles according to the standards for rotation sequences of the International Society of Biomechanics. Joint angles are extracted as Euler angles with Z as flexion/extension, X as abduction/adduction, and Y as internal/external rotations, where the hip is the joint between the pelvis and upper leg, and the knee is the joint between the upper leg and the lower leg (XSens Technologies, 2020).

Therefore, knee and hip joint angles around the Z-axis in positive direction (= flexion) and knee joint angles around the X-axis in negative direction (= adduction) were exported into MATLAB (R2018b, The MathWorks Inc., Natick USA) for further analysis. First the start and end of each exercise, defined as the point where the participant is closest to a neutral, upright standing position (knees and hip fully extended, feet touching the ground and hip width apart, equally distributed weight) was determined through video analysis. All exercises which were visually correctly performed, even when the ExerCube did not consider them as correct (for example due to wrong timing), were used for analysis. In order to align the video data and the joint angle data, the frame difference between the two systems was calculated by comparison of the deepest point of the first squat in the video and the highest knee flexion angle. Even though the sampling frequency of each system was 60 Hertz, they did not transmit data at this constant rate. Therefore, the frame difference was calculated again for the last squat for comparison. Then the joint angle data of each lower body exercise (Squat, Jump, Lunge Right, Lunge Left, Burpee) was extracted and tested for plausibility. All non-plausible data or data where crosstalk was visible, was excluded. Since the pelvis belt rode up during the ExerCube training of all participants, its data is not reliable anymore. Therefore, the hip flexion angle was only qualitatively examined through video analysis. Data of five participants had to be excluded completely. In all of the remaining seven participants, crosstalk or non-plausible data was found in the data of one leg, which was excluded as well (final sample size: right leg n = 5, left leg n = 2). Due to implausible data with possible interactions of the XSens system and the tracking system of the ExerCube (HTC Vive), the burpees of all participants were excluded for analysis. Except the lunge, where a distinction between front leg and back leg was made, all exercises were assumed as symmetrical. Therefore, data of one leg was considered enough for analysis. For each exercise it was determined which percentage of time the knee flexion angle was in the range between 10° to 30°. Additionally, the number of milliseconds during which the participant was in the susceptible knee flexion angle, was calculated for every exercise. In each exercise the peak adduction angle was found and considered for analysis.

2.5 Statistics

Statistics were calculated with R (Version 4.0.3, The R Foundation for Statistical Computing) and RStudio (Version 1.3.1093, RStudio PBC). For analysis of the effects of the ExerCube training on movement quality (knee flexion angle and knee adduction angle), a two-way within subject linear mixed model was used. It was assumed that the variables are normally distributed, and the fixed effects are time and exercise. This assumption was checked with a plot of the residuals. Since the number of datasets used for analysis is large, the assumption of the central limit theorem can be considered true. Several polynomial models of time with different degrees were made and compared with an ANOVA. The model, which fitted the real data the best was chosen for analysis. In order to compare the different exercises, contrasts were calculated. The level of significance was chosen as $p < 0.05$.

To assess differences of the H/Q-ratio of the dominant and the non-dominant leg, a paired t-test was performed. Additionally, the relative peak torque of the knee flexor and the knee extensor was compared between the dominant and the non-dominant leg with a paired t-test. Since there are only 12 participants, normal distribution of the data was assessed with a Shapiro-Wilk test which showed no significant difference. Furthermore, it was assessed whether data is skewed. This was not the case. In order to be significant, the p-value of a test had to be smaller than 0.05.

3. Results

3.1 ExerCube Training

3.1.1 Knee Flexion Angle

The mean amount of time during which the knee flexion angle was between 10° and 30° varied between the exercises (Table 2). Most notably are the differences between the front and back leg of the left lunge, as well as front and back leg of the right lunge.

Table 2: Mean time of the knee flexion angle in the susceptible range of 10° - 30° for each exercise.

Exercise (number of measurements)	Mean time [ms] with knee flexion angle between 10° and 30° ± SD
Jump (n = 432)	493.40 ± 189.71
Lunge Left: front leg (n = 16)	392.16 ± 144.95
Lunge Left: back leg (n = 38)	1541.67 ± 1986.74
Lunge Right: front leg (n = 33)	1108.33 ± 1500.85
Lunge Right: back leg (n = 14)	342.86 ± 217.77
Squat (n = 390)	392.91 ± 275.89

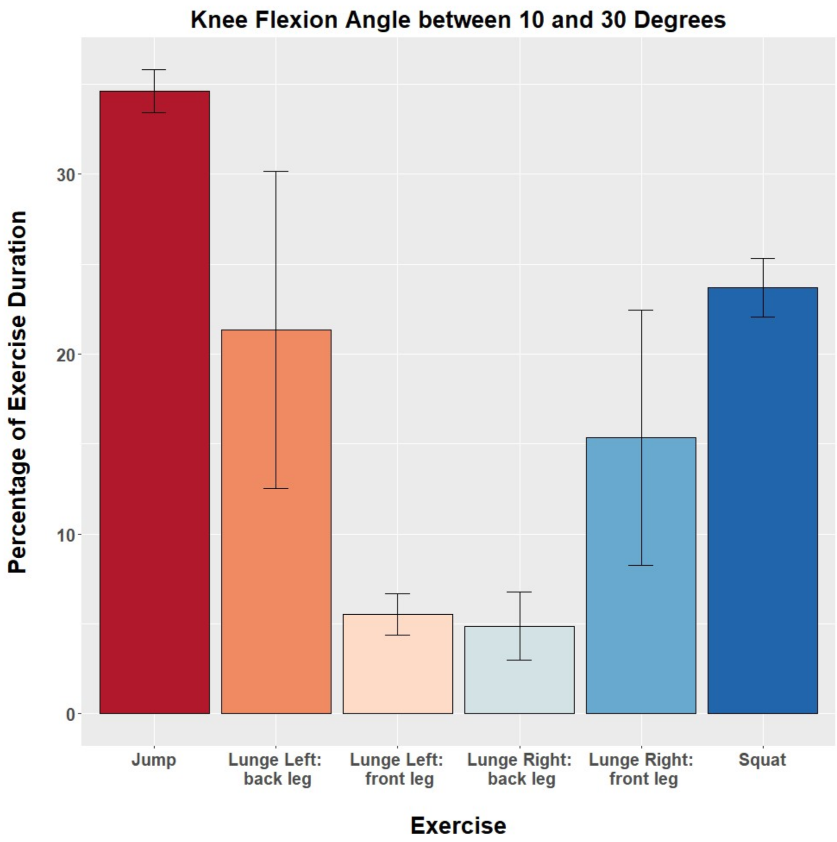

Figure 5: Mean percentage of exercise duration in which the participants were in the susceptible knee flexion angle.

Figure 5 shows the amount of time during which the participant's knee flexion angle was in the susceptible range (between 10° and 30°) in comparison to the duration of the exercise. Even though the mean time in milliseconds suggests the back leg of the left lunge and the front leg of the right lunge were in the susceptible range the most, when the percentage is considered this observation is not true anymore (Figure 5). During the jump the knee was in the susceptible range in 34.61% of the whole exercise duration, which was the highest percentage of all exercises. The squat and the back leg of the left lunge were in the susceptible range for 23.68% respectively 21.35% of the total duration, while the front leg of the left lunge and the back leg of the right lunge were only 5.54% respectively 4.87% of the total duration in the susceptible flexion angle.

No significant differences could be detected between jump and all the other exercises (jump vs. front leg of the right lunge p = .78, jump vs. back leg of the right lunge p = 1.00, jump vs. front leg of the left lunge p = 1.00, jump vs. back leg of the left lunge p = .55, jump vs. squat p = 1.00). The squat did not reveal any significant differences when compared to the front (p = 1.00) or back leg (p = .42) of the left lunge, nor in comparison to the front (p = .65) or back leg (p = 1.00) of the right lunge. Between the back and front leg of the right lunge (back leg vs. front leg p = .91) and the left lunge (back leg vs. front leg p = .84), no significant differences exist. Comparison of both the back leg between the right and left lunge (p = .80), and the front leg between the right and left lunge (p = .93) resulted in no significant differences. No significant difference as well was found in the comparison of the front leg of one side of the lunge with the back leg of the other lunge side (front leg left vs. back leg right p = 1.00, front leg right vs. back leg left p = 1.00).

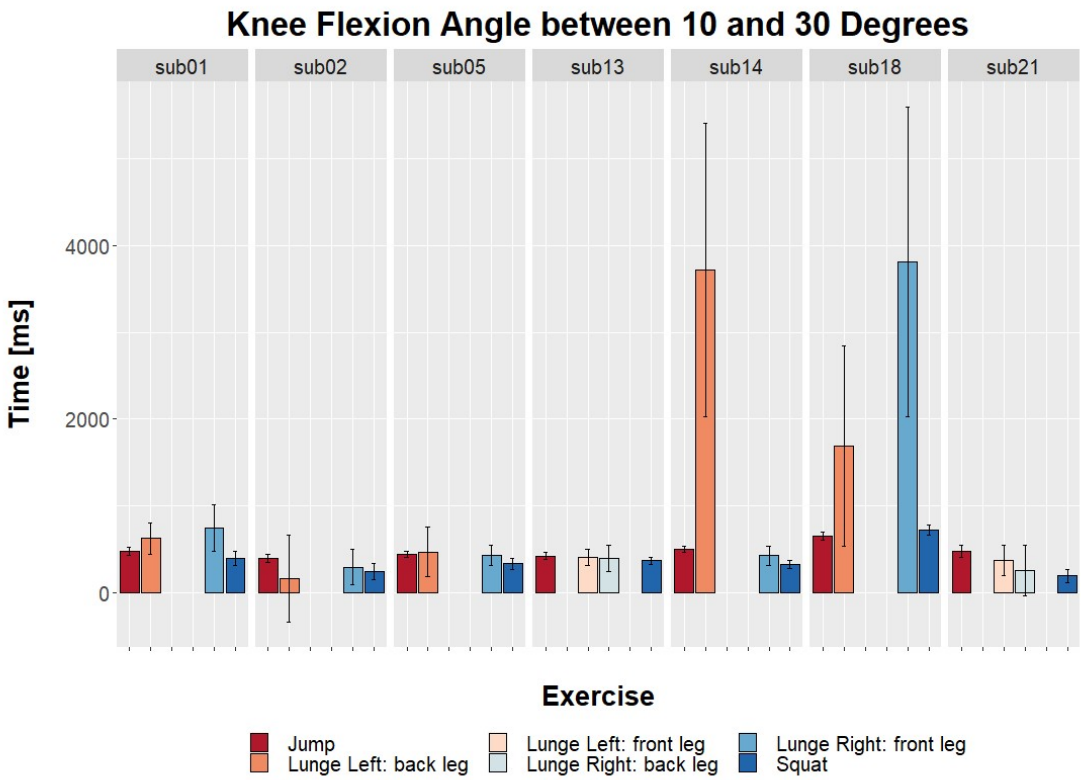

Figure 6: Mean time in the susceptible knee flexion angle for each subject.

Differences in the time during which participants were in the susceptible knee flexion angle were present (Figure 6). Whereas for the jump, front leg of the left lunge, back leg of the right lunge, and squat, no big difference can be detected visually between the participants, for the back leg of the left lunge and the front leg of the right lunge a difference from the other participants can be clearly seen in subject 14 and subject 18.

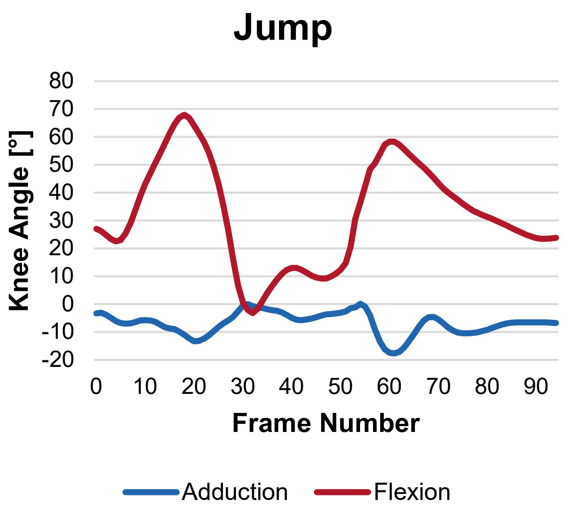

Figure 7: Example of the knee flexion and the knee adduction angle of the right leg during a jump.

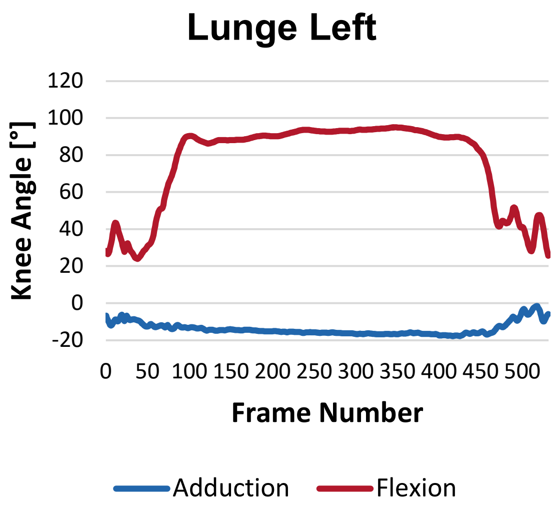

Figure 8: Example of the knee flexion and the knee adduction angle of the right (back) leg during a left lunge.

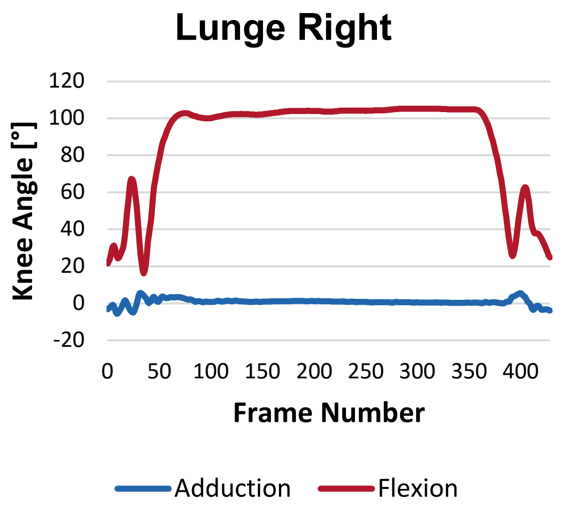

Figure 9: Example of the knee flexion and the knee adduction angle of the right (front) leg during a right lunge.

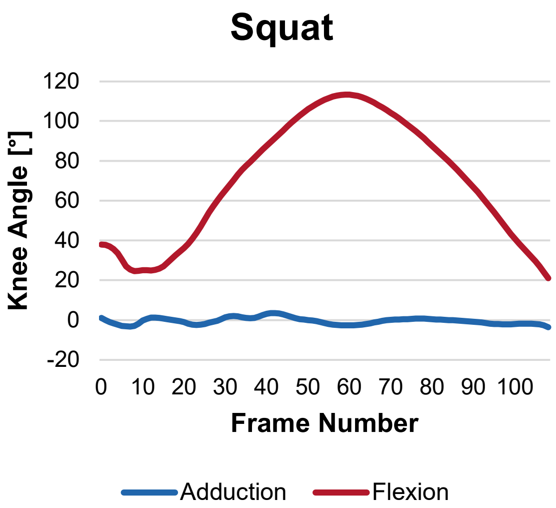

Figure 10: Example of the knee flexion and the knee adduction angle of the right leg during a squat.

The knee flexion angle, as well as the knee adduction angle of an example exercise of subject 1 can be seen in figure 7, figure 8, figure 9, and figure 10. During the lunges and the squat, knee flexion angles reached maximal values over 100°, while during the jump a maximal knee flexion angle only slightly bigger than 60° was measured. The duration of the lunges, with over 450 frames, which equals more than 7500 milliseconds, was much higher than the duration of the jump and squat, which was approximately 100 frames (= 1667 milliseconds).

3.1.2 Knee Adduction Angle

A small difference between the exercises can be seen for the mean adduction angle of all participants (Table 3). Whereas the mean adduction angle for the back leg of the left lunge is much lower than the adduction angles for the right lunge, the mean adduction angle of the front leg of the left lunge is much higher than the adduction angles for the right lunge.

Table 3: Mean knee adduction angle of all participants for each exercise in degrees.

Exercise (number of measurements)	Mean adduction angle [°] ± SD
Jump (n = 432)	11.99 ± 9.31
Lunge Left: front leg (n = 16)	36.18 ± 5.44
Lunge Left: back leg (n = 38)	5.18 ± 6.35
Lunge Right: front leg (n = 33)	20.47 ± 16.44
Lunge Right: back leg (n = 14)	20.30 ± 18.74
Squat (n = 390)	24.14 ± 16.93

The differences in the knee adduction angle between jump and back leg of the left lunge ($p = 1.00$), jump and back leg of the right lunge ($p = .96$), back leg of the left and right lunge ($p = .96$), front leg of the left and right lunge ($p = 1.00$), plus front leg of the left lunge and back leg of the right lunge ($p = .55$) were not significant. No significant differences were found as well between the squat and front leg of the left lunge ($p = .91$), front and back leg of the right lunge ($p = .79$), back leg of the right lunge and squat ($p = .95$), and front leg of the right lunge and squat ($p = .95$). Differences between jump and front leg of the left lunge ($p = .12$), back and front leg of the left lunge ($p = .18$), jump and squat ($p = .10$), and back leg of the left lunge and squat ($p = .14$) are more likely, although not significant. Two comparisons (jump vs. front leg of the right lunge $p = .04$, back leg of the left lunge vs. front leg of the right lunge $p = .04$) led to significant differences.

3.1.3 Trunk Inclination Angle

A qualitative video analysis revealed that, even though the movement pattern differed between each participant and each exercise, during the squat all participants tilted their pelvis. Two participants (subject 2 and subject 9) lifted their heels off the ground when performing the squat. Six participants did not tilt their pelvis visibly when jumping, while five participants slightly tilted their pelvis, either during the countermovement or the landing phase. Only one participant did a squat (with hands beneath the ankles) as countermovement of the jump and therefore had a clearly visible trunk inclination. Most differences were observed during lunges, even within the same participants. When the system did not recognise the lunge, participants moved their trunk a lot in order to find the spot where the system registers the lunge. Therefore, no clear statement can be made for the lunges.

3.2 Strength Measurement

The mean H/Q peak torque ratio for the dominant leg was 71.0% ± 9.65% and for the non-dominant leg 73.75% ± 14.56%. No significant differences of the H/Q peak torque ratio between the dominant and the non-dominant leg were found ($t\ (11) = -0.67$, $p = .52$).

The mean relative peak torque for the knee flexor of the dominant leg was 144.58% $Nmkg^{-1}$ ± 10.40% $Nmkg^{-1}$ and for the non-dominant leg it was 145.85% $Nmkg^{-1}$ ± 16.90% $Nmkg^{-1}$. For the relative peak torque of the knee extensor mean values were 205.50% $Nmkg^{-1}$ ± 27.32% $Nmkg^{-1}$ for the dominant leg and 201.42% $Nmkg^{-1}$ ± 32.37% $Nmkg^{-1}$ for the non-dominant leg. When the relative peak torque values of the dominant and the non-dominant leg were compared, neither for the knee flexor ($t\ (11) = -0.31$, $p = .76$), nor for knee extensor ($t\ (11) = 0.67$, $p = .52$), a significant difference was found.

4. Discussion

4.1 ExerCube Training

4.1.1 Jump

The highest percentage of the total duration of the exercise, during which participants were in a knee flexion angle between 10° and 30°, was found in the jump. It is most likely that participants had low flexion angles during the propulsion phase (between the bottom of the countermovement and the take-off including forceful extension of hips, knees and ankles), as well as the early landing phase (Figure 7). Especially the landing phase, or more specifically the position of the knee when landing, is crucial for ACL injury risk since a typical non-contact injury occurs when landing from a jump with the knee near full extension and in a valgus position (Kaeding et al., 2017; Leppänen, Pasanen, Kujala, et al., 2017). When landing, participants often had a small knee flexion angle and their upper body was upright. This suggests a high load on the ACL. Whereas the peak adduction angle, which represents the knee valgus, peaked during the countermovement and the post-landing phase and was around zero during the transition phases, does not add to a higher risk for ACL re-rupture (Figure 7).

Even though the representations of knee flexion and adduction angle in the example exercise of subject 1 (Figure 7) do not suggest it, it is possible that the cognitive task of the ExerCube and the physical challenge (due to previous and following exercises) led to altered pre-landing biomechanics with a peak strain on the ACL during pre-landing as in the study of Dai et al. (2018). Additionally, the level of the ExerCube, which determines the speed of the exercise sequence, could play a role in ACL injury risk since according to Escamilla et al. (2012) higher deceleration results in bigger ACL loading. The load on the ACL could be reduced by a proper landing technique which includes adequate knee flexion, forward trunk tilt, controlled knee valgus, hip adduction, and internal rotation (Escamilla et al., 2012; Leppänen, Pasanen, Krosshaug, et al., 2017).

Because an increased trunk flexion when landing leads to increased muscle forces of the hamstrings and gluteus maximus which in turn reduces knee extension and valgus moment associated with decreased loading on the ACL (Hughes, 2014), it is favourable to land with an inclined trunk. Observations through video analysis found that participants did not execute the landing in a favourable way, which could increase ACL injury risk.

The collected data suggests that both investigated risk factors for an ACL injury are present when performing the jump during the ExerCube training. Therefore, especially during the early phases of rehabilitation, it is not recommended to perform this exercise. During later stages of the rehabilitation, the exercise may be performed with low speed and adequate teaching of the proper landing technique. Additionally, a supervisor (e.g. physical therapist) should be present in order to remind the patient of the correct landing technique in case the patient gets distracted by the game or the competition associated with it.

4.1.2 Lunges

The flexion angle of the back leg increased steadily until the final position of the lunge is reached (Figure 8). In contrast, the front leg flexion angle first increased when lifting the foot off the ground for the forward step and then decreased when the weight was shifted forward. Afterwards it increased steadily until the final position of the lunge was reached (Figure 9). When returning to the upright standing position from the lunge, both the back leg and the front leg first decreased in knee flexion angle and then increased again when the step back was made. A big difference in the mean knee flexion angle was found between the front and back leg of both lunges. This difference could be explained by different techniques because data for the front leg and the back leg is from different participants. Two participants had a much higher number of milliseconds in the susceptible knee flexion angle range, which can be attributed to different techniques as well (Figure 6). The affected participants either flexed the knee of the front leg to a great extent while having their back leg almost at full extension (subject 14) or only slightly flexed both knees (subject 18). In contrast, other participants mainly flexed their back leg while the front leg was almost fully extended, or they flexed both knees to the same extent. Therefore, it is likely that a great variability in technique resulted in different results or even led to a shift of the mean. Furthermore, the amount of data sets for lunges, especially for the front leg of the left lunge and the back leg of the right lunge with data from two participants, was very low. Also, the other lunge variables did not have a high quantity of data from only five participants. Results of the lunges have therefore to be interpreted with caution.

Knee adduction angles of the left lunge differed greatly between the front and the back leg which can likely be attributed to different techniques. Additionally, balance problems may likely have influenced knee adduction angles. When the leg is stretched, balance problems are less likely to occur. Because the two participants with almost fully extended back legs (subject 14 and subject 18) were part of the group for the back leg of the left lunge, the adduction angle there might be so low. On the other hand, the data for the front leg of the left lunge consisted only of data from two participants, who may have had balance problems and shifted their knee to the right and left. This might result in such a big mean angle. In the right lunge, the mean adduction angles of the back leg and the front leg were almost identical. This suggests a symmetrical movement of both legs in the lateral direction from different participants. When no balance problems occurred, the knee adduction angles were almost constant during the whole duration of the lunge (Figure 8, Figure 9). It can be noted that a small abduction of the back leg (left lunge) occurred while a small adduction of the front leg (right lunge) occurred in the example participant.

Movements of the trunk during performance of the lunge in both, the right and the left corner, varied greatly between and within the participants. Even though, co-activation of the hamstrings can be assumed during a lunge, no clear statements regarding trunk flexion angle can be made.

Although there is a statistically significant difference between the back leg of the left lunge and the front leg of the right lunge, as well as between the jump and the front leg of the right lunge, it must be interpreted cautiously due to the low amount of data. The difference between the back leg of the left lunge and the front leg of the right lunge could be explained by a stable back leg of the left lunge and an unstable front leg of the right lunge, for example due to balance problems. Landing from a jump may be an anticipated movement and therefore result in smaller peak adduction angles. Furthermore, the front leg of the right lunge could have been very unstable in the lateral direction. These are two potential explanations of the significant difference between the jump and the front leg of the right lunge. Additionally, during the jump the ExerCube recognises the lifted arms in the flight phase which means the athlete can fully concentrate on a correct landing, while during the lunge, the arms have to be in the optimal position in the ExerCube space and in front of the chest for the system to recognise it. Therefore, the participant might be concentrating on the correct arm position during the lunge and not be aware of the position of the legs.

Even if the participants used different techniques, Escamilla et al. (2012) stated that ACL loading is minimal during the forward lunge. This fact is supported by the low percentage of the whole exercise duration during which the knee flexion angle was between 10° and 30°. When no balance problems occurred during the lunge, the knee flexion angle and knee adduction angle remained constant as soon as the participant was in the correct position (Figure 8, Figure 9).

Since only a very low amount of time is spent in the susceptible knee flexion angle range and the lunge can be performed without having as much time pressure as in all other exercises, it should also be possible to perform when rehabilitating from an ACL injury. Because early after surgery, due to swelling, the ROM of the knee is not high enough to perform the lunge, it is recommended that this exercise is performed as soon as the required flexion range can be achieved.

4.1.3 Squat

Because the squat is such a quickly performed exercise, even though the mean time in the susceptible knee flexion angle was low, the percentage of the whole exercise duration in the susceptible angle for the squat had the second highest number. The example participant had a slightly increased flexion angle at the beginning of the exercise which shortly decreased before it increased again (Figure 10). This was because the example participant did a step to the left to increase the distance between the feet before squatting down which resulted in the slightly bigger flexion angle of the right leg at the beginning of the exercise. When the optimal position for the squat was reached, the knee flexion angle increased steadily until the hands were touching the ground. Then it decreased continuously until the body was in an upright position. Small differences between the participants exist which can be attributed to difference techniques. Some participants sat down on their heels while simultaneously lifting the heels off the ground, and others showed great flexibility because they touched the ground with hardly any flexion of the knee. These technique variations could lead to a different loading on the ACL. Primarily, lifting the heels off the ground which leads to a big forward knee movement beyond the toes and a greater knee flexion angle, could increase the load on the ACL over three times when compared to a squat with the heels on the ground (Escamilla et al., 2012).

Even though figure 10 suggests that the knee adduction angle was constant during the whole duration of the squat, the mean peak knee adduction angle of all participants was much higher. This could be attributed to different techniques as mentioned above. Another possible influence factor could be that the different systems (HTC Vive trackers and XSens sensors) influenced each other due to close proximity to one another when in a squat, even though no systematic measurement error could be detected in the plausibility graphs. An almost significant difference was found between the jump and the squat, which might have resulted from either different techniques and the great variation resulting from it or from the anticipation of the landing which was present in the jump while during the squat participants already concentrated on the next exercise.

All participants, except the two who sat on their heels when squatting, had a clearly inclined trunk. While doing a squat with a tilted trunk leads to a decrease of ACL loading, doing a squat with an upright trunk results in more loading on the ACL (Escamilla et al., 2012). This is likely due to the fact that hamstrings are activated when the trunk is tilted forward while quadriceps muscles are more activated when the trunk is upright (Ohkoshi, Yasuda, Kaneda, Wada, & Yamanaka, 1991).

Overall, the squat does not lead to high strain on the ACL, especially when the trunk is tilted forward to decrease loading and can therefore be performed during rehabilitation after ACLR. Since the ROM early after surgery is decreased and the ExerCube might not recognise a squat with a limited ROM, it is not recommended during early stages of rehabilitation. During later rehabilitation phases the squat is a suitable exercise. Because the ExerCube environment leads to an external focus of attention, participants have to be carefully instructed on how to perform the exercises correctly because the technique is crucial to ACL loading. Furthermore, the speed of the ExerCube may have to be reduced that the athlete has enough time to focus on the performance of the exercise and does not have to rush uncontrollably into the next exercise.

4.2 Strength Measurement

Other studies (Andrade Mdos et al., 2012; Buchanan & Vardaxis, 2009; Lund-Hanssen, Gannon, Engebretsen, Holen, & Hammer, 1996; Pincivero, Gandaio, & Ito, 2003; Risberg et al., 2018) investigating recreational and elite female athletes of basketball, handball, soccer, or various types of sport, found H/Q-ratios ranging from 50 - 59.4%. Therefore, the mean H/Q-ratio of this study population was much higher which means that the mean peak knee flexor strength of this study population was higher than average, or the mean peak knee extensor strength was lower. Comparison of the absolute and relative knee strength revealed that the participants in this study had lower peak knee extensor strength and similar peak knee flexor strength than the reference population of elite athletes (Risberg et al., 2018). A reduced knee extensor strength is not favourable for ACL injury risk because it limits the potential to protect the ligaments through co-contraction (Hewett et al., 2006). The reduced knee extensor strength could also be due to the effect of gravity, which was not corrected by the dynamometer. Reference studies found only a small or no difference between the dominant and the non-dominant leg which coincides with the results found in this study. This also supports the assumption of symmetry which was made. However, results for the non-dominant leg were slightly higher which could be due to the learning effect since the non-dominant leg was tested after the dominant leg. Additionally, three trial repetitions could have been too little to accustom to the testing procedure and testing conditions which may have led to lower strength results, or three repetitions may not have been enough to reach peak strength values.

4.3 Limitations and Outlook

Several limitations were present in this study. Biomechanical risk factors were only analysed during the exercises and not during the time between the exercises, where the risk factors could be present as well. Additionally, symmetry of both legs when performing the movements had to be assumed because data of only one leg could be analysed which in turn led to a lower amount of data and therefore low generalization of the results. There are other unknown factors like motivation and physical or cognitive fatigue which could have influenced the movement quality. Even though it is known that the ExerCube environment is generally motivating (Martin-Niedecken et al., 2019), the fact that the system sometimes did not recognise the exercise, although it seemed to be performed correctly, could have demotivated participants. Another potential demotivator could have been that the system slowed down when an exercise was not performed correctly. Effects of fatigue were not investigated, but it is possible that its effect was compensated by more mistakes of the participants which then led to slowing down of the pace at which new exercises appeared in the ExerCube or that fatigue led to a decreased movement quality and therefore altered biomechanics. Because no balance of the type of sports is present in the study population, different experience, training regimens, or demands of a type of sport could have led to confounded results. On the one hand for example in volleyball, players often perform jumps while shuffle steps are not performed often and on the other hand floorball players frequently use shuffle steps while jumps are performed infrequently. Another limitation was the duration of the continuous measurement (25 minutes), which resulted in drift of the XSens position data (same drift for all sensors). Furthermore, even though the sensors were firmly attached to the skin, their position could have changed slightly during the measurement session which could have resulted in inaccurate measurements. The start and end of each exercise was determined through video analysis which might have led to investigator bias. Moreover, the XSens measuring system did not always transmit the data at a constant rate while the video camera recorded constantly, which resulted in a frameshift. Although this frameshift was corrected, it might not be perfectly accurate and have resulted in slightly skewed data. Besides, hormonal levels and therefore the ROM of the knee or knee laxity could have differed between the participants and resulted in different movement patterns. Limitations of the strength measurements were that the effect of gravity was not corrected and that only three repetitions were made at each angular velocity. Overall, a low amount of data was analysed which is normal for a pilot study, but it results in the fact that the data has to be interpreted cautiously.

To determine whether a training in the ExerCube is safe and suitable for patients after ACLR, more research is needed. The biomechanics of the knee between the different exercises has to be investigated as well as the biomechanics of the knee during the exercises with more participants. Additionally, it would be favourable not to manually determine the beginning and end of each exercise since this may lead to investigator bias. Due to different movement patterns after ACLR, an investigation of the biomechanics of the knee as well as pain levels during the ExerCube training with former ACL injury patients who already returned to sports is needed. Furthermore, movement patterns of the hip and ankle may influence knee biomechanics and have therefore to be investigated as well. Strength of the knee flexor and extensor is lower after ACLR compared to healthy participants, which also might play a role in the biomechanical movement patterns. Depending on the type of graft used, muscle recruitment could be different. For example with the hamstrings graft, knee flexor strength is reduced for up to 24 months after the surgery (Pappas, Zampeli, Xergia, & Georgoulis, 2013). Therefore, co-activation of the hamstrings is not favoured even though it decreases ACL loading. Hence, further investigations after ACLR including type of graft used and strength assessments are needed to determine the safety of the ExerCube training during ACL rehabilitation. Additionally, a study including only participants of the same sport could give insight into previously trained sport-specific mechanisms and reduce differences of physical and cognitive demands specific to one type of sport.

Conclusion

The aim of this thesis was to conduct a biomechanical quality assessment during an ExerCube training by investigating two biomechanical risk factors and a biomechanical protective factor for an ACL (re-) rupture. It can be concluded that even though in all exercises the knee flexion angle was in the susceptible range, a knee valgus position was present, and the trunk was not inclined enough, during later stages of rehabilitation and with supervision, the squat and lunges should be safe to be performed by patients. Both exercises can be performed with a high amount of neuromuscular control and the body weight is distributed between the healthy and the injured leg which leads to a smaller load on the injured ACL. The amount of available data for the lunge was low, which leads to a low generalizability. According to literature the squat should be safe to be performed during rehabilitation after ACLR, but the different circumstances of the ExerCube environment lead to small risks. The jump has the highest amount of risk since it does fulfil the two investigated risk factors (knee flexion angle between 10° and 30°, knee adduction angle) and does not fulfil the protective factor (trunk inclination angle between 30° and 40°). The time between the exercises, when the speed is high, could even be riskier because movements are often uncontrolled, and participants jump from side to side. Due to the high acceleration, explosive movements create high muscular effort and potentially increase the loading of the ACL, especially at low knee flexion angles. This leads to the conclusion that the jump is the most dangerous exercise. However, biomechanical and muscular properties differ greatly between the healthy participants of this study and patients after ACLR. Healthy participants have higher muscle strength, different movement patterns, and a full ROM since no swelling or pain restricts movements. Therefore, the results cannot be directly translated to rehabilitating patients. Many factors which potentially play a role in movement quality and biomechanics of the lower body during an ExerCube training remain unknown and have to be further investigated in order to determine if an ExerCube training is applicable during ACL rehabilitation. But it provides great potential since many factors currently lacking in rehabilitation programs such as training of reaction time or visual-motor control is possible with the ExerCube.

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Appendix

Appendix A: ExerCube Training Session

Figure 11: Tracker position on the ankle (left) and wrist (right). (spheryfitnessgaming, 2020)

Figure 12: Calibration of the HTC Vive system. (spheryfitnessgaming, 2020)

Figure 13: ExerCube just before the start. (spheryfitnessgaming, 2020)

All exercises start and end in the centre of the ExerCube at the level of the touch points.

Table 4: Description of the different exercises performed during an ExerCube training. (spheryfitnessgaming, 2020)

Exercise Name	Description of Movement	Picture
Touch	• Sidestep to the right or left wall • Touch of the right or left wall in the middle of the wall's height • Sidestep back to the centre	
Low Touch	• Sidestep to the right or left wall • Touch of the right or left wall at the bottom of the wall's height • Sidestep back to the centre	
High Touch	• Sidestep to the right or left wall • Touch of the right or left wall at the top of the wall's height • Sidestep back to the centre	
Squat	• Sumo squat in the centre of the ExerCube space with hands touching the ground between the legs • The upper body is kept straight	
Jump	• Stretch jump in the centre of the ExerCube space with use of the swing of the arms to jump as high as possible	

Burpee	•Jump into the air with both hands as high as possible •Going directly into the plank position •Holding the position until the speaker says “get up now”	
Tripples	•Sprint with arms and legs on the spot (centre of the ExerCube space) •The more evenly the movement is, the faster the progress bar fills up	
Punch	•Sidestep to the right or left wall •Rotation of the upper body •Punching of the wall at the middle target •Sidestep back to the centre	
Lunge	•Aiming at the corner with the respective foot and holding the arms in place with the hands in front of the chest •Position of the upper body is at the level of the targets	

Figure 14: Finish of the ExerCube training. (spheryfitnessgaming, 2020)

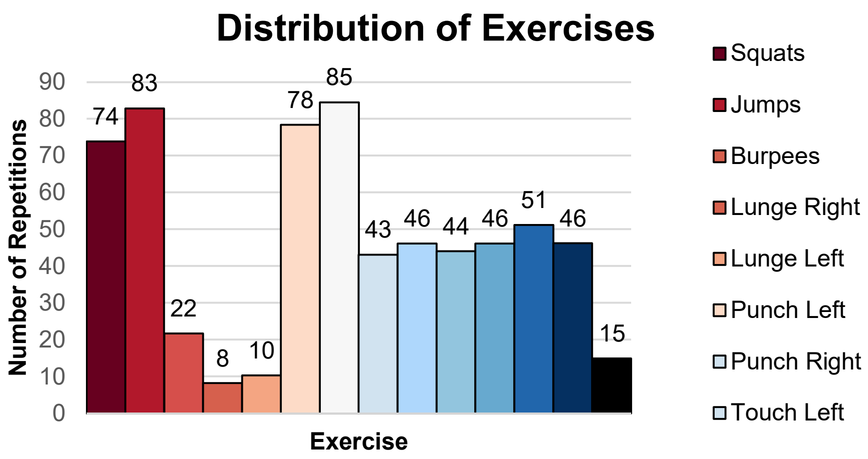

Figure 15: Mean number of repetitions per exercise of all participants.

Appendix B: Participant Information and Informed Consent

Zürcher Hochschule für Angewandte Wissenschaften

zh aw Gesundheit

Biomechanische Analyse von ausgewählten Risiko- und Schutzfaktoren für einen Kreuzbandriss während eines Trainings mit dem ExerCube

Biomechanical Analysis of Selected Risk and Protective Factors for an Anterior Cruciate Ligament (Re-) Rupture during a Training with the ExerCube

Dieses Projekt ist organisiert durch: ZHAW Zürcher Hochschule für Angewandte Wissenschaften

Liebe Sportlerin,

Wir möchten Sie anfragen, ob Sie an einem Forschungsprojekt teilnehmen wollen. Im Folgenden wird Ihnen das geplante Forschungsprojekt detailliert dargestellt.

1. Ziel des Projekts
Das Forschungsprojekt untersucht die Biomechanik während eines Trainings mit dem ExerCube, einem Videospiel-basierten Trainingsgerät, bei gesunden Athletinnen. Ziel ist es, mittels biomechanischer Winkelmessungen der Kniebiegung, des Oberkörpers und des Einknickens des Knies herauszufinden, ob sich die ExerCube-Umgebung auf die Bewegungsqualität auswirkt. So soll dieses Projekt Aufschluss darauf geben, ob es denkbar und sicher ist ein Training mit dem ExerCube während der Rehabilitation durchzuführen.

2. Auswahl
Es können alle gesunden, weiblichen Personen teilnehmen, die zwischen 18 und 50 Jahre alt sind und mindestens 2x1h pro Woche eine der folgenden Sportarten in einem Verein betreiben: Basketball, Fussball, Handball, Unihockey oder Volleyball. Ausserdem sollten Sie sich zum Zeitpunkt der Messungen zwischen Tag 0 (Beginn der Menstruation) und 12 (Eisprung) des Menstruationszyklus befinden. Wenn Sie hormonell verhüten, dürfen Sie trotzdem an der Studie teilnehmen. Falls Sie eines der folgenden Kriterien erfüllen, sind Sie für eine Teilnahme NICHT geeignet:

- Schwangerschaft oder wenn Sie stillen
- Verbot eines Arztes hochintensives Training zu absolvieren
- Vorherige Operationen an den Beinen
- Vorheriger Kreuzbandriss

3. Allgemeine Informationen zum Projekt
Ein Kreuzbandriss ist eine der häufigsten Sportverletzungen, vor allem bei Frauen ist dieser häufiger als bei Männern. Die Rehabilitation nach einer solchen Verletzung dauert circa 6 Monate und erfordert viel Physiotherapie mit sich häufig wiederholenden Übungen. Dies kann zu einer tiefen Motivation führen, was wiederum zu einem schlechteren Ergebnis der Therapie führt. Sowohl Umweltfaktoren wie Bodenbeschaffenheit, als auch körperlich bedingte Faktoren wie zum Beispiel Hormone oder die Kraft der Oberschenkelmuskulatur können Risikofaktoren für einen Kreuzbandriss darstellen.
Der ExerCube ist ein interaktives Fitnessspiel, dass sowohl das Gehirn als auch den Körper trainiert. Durch die Anstrengung des Gehirns leidet häufig die Qualität von Bewegungen, was dazu führen könnte, dass das Verletzungsrisiko bei Patienten in der Rehabilitation grösser wird. Das Auftreten der erwähnten Risikofaktoren soll bei gesunden Athletinnen während eines Trainings mit dem ExerCube erfasst werden, um zu erforschen wie sich die ExerCube-Umgebung auf die Qualität der Bewegungen auswirkt.
Es werden zwei Arten von Messungen gemacht: Kraftmessungen und Messungen der Biomechanik im ExerCube. Die Kraftmessungen werden in der Medbase WIN4 in Winterthur stattfinden und die Messungen der Biomechanik im WIN4 Winterthur oder bei Sphery Ltd. in Zürich. Sie sind zwischen August und Oktober 2020 geplant. Jede Teilnehmerin absolviert eine

Kraftmessung und eine Messung der Biomechanik innerhalb von 12 Tagen. Insgesamt sollen 20 Sportlerinnen getestet werden.
Dieses Projekt wird so durchgeführt wie es die Gesetze in der Schweiz vorschreiben. Die kantonale Ethikkommission des Kantons Zürich hat das Projekt geprüft und sich als nicht zuständig erklärt.

4. Ablauf

Das Projekt wird folgendermassen ablaufen:

1. Rekrutierung und Eignungsabklärung
2. Teilnehmerinformation und Einverständnis
3. Ausfüllen des Fragebogens und Kraftmessung
4. Mind. 24h Erholungszeit
5. Messung der Biomechanik im ExerCube

Nachdem Sie Ihr Interesse an einer Studienteilnahme ausgedrückt haben, werden wir Sie via Telefon oder E-Mail kontaktieren, um Sie sowohl über den Studienablauf zu informieren als auch Ihre Eignung abzuklären. Danach werden Termine für beide Messungen vereinbart. Am ersten Messtermin wird, sobald Sie ihr Einverständnis zu einer Teilnahme gegeben haben, geprüft, ob alle Eignungskriterien erfüllt sind. Falls Sie nicht geeignet sind, werden alle bis dahin gesammelten Daten unverzüglich gelöscht. Wenn Sie sich für ein Teilnahme eignen, füllen Sie am Studienort einen Fragebogen zu personenbezogenen Daten, Ihrer Sportart und früheren Verletzungen aus, bevor die Kraft der vorderen und hinteren Oberschenkelmuskulatur mit einem Kraftmessgerät gemessen wird. Es wird zuerst das stärkere und nach einer 5min langen Pause das schwächere Bein gemessen. Die Aufgabe wird vor der Ausführung nochmals genaustens erklärt und vorgeführt. Die erste Messung wird ca. 1h dauern. Nach dieser Messung haben Sie mindestens 24h Zeit sich zu Erholen.
Nach der Erholungszeit werden Sie für einen zweiten Messtermin eingeladen. Bitte finden Sie sich dann am Studienort ein und bringen Sie kurze Sporthosen und Hallenschuhe mit. Das Tragen von kurzen Hosen ist für die Messung notwendig, da Sensoren mittels einem Klettband an die Hüfte, die Oberschenkel und die Unterschenkel angebracht werden. Sobald Sie sich umgezogen haben und bereit sind für ein Training im ExerCube (Abbildung 2), werden mit einem Klettband Sensoren an den Hand- und Fussgelenken befestigt und ein Pulsgurt wird angelegt. Sobald das System des ExerCubes ausgerichtet ist, startet ein 3-minütiges Eingewöhnungstraining, in dem alle durchzuführenden Bewegungen geübt werden können. Anschliessend wird das Messsystem für die Messung der Kniewinkel, Einknicken der Knie und dem Oberkörper-Winkel, angelegt und erneut ausgerichtet. Sobald alles fixiert ist, startet das ca. 25-minütige ExerCube Trainingsprogramm. Nach dem Training werden alle Sensoren wieder entfernt. Die zweite Messung wird ca. 1-1.5h dauern.
Insgesamt beträgt der Zeitaufwand für die Studie 2-2.5h. Sollten Sie während irgendeines Tests Schmerzen haben oder sich aus anderen Gründen unwohl fühlen, informieren Sie uns bitte. Die Messung kann jederzeit abgebrochen werden. Eine Übersicht über den Ablauf der Messtermine kann in Abbildung 1 gefunden werden.

Abbildung 1: Übersicht über den Ablauf der Messtermine. (Quelle: Eigene Darstellung)

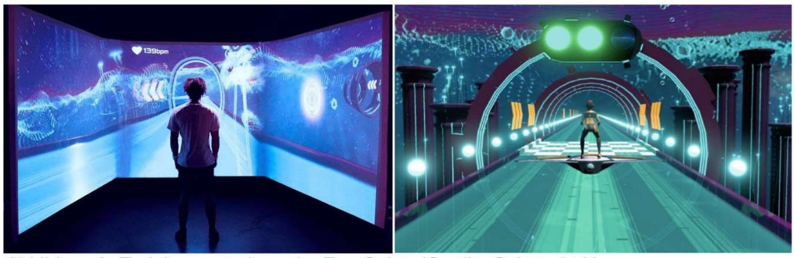

Abbildung 2: Trainingsumgebung im ExerCube. (Quelle: Sphery Ltd.)

5. Nutzen
Sie werden persönlich keinen Nutzen von der Teilnahme am Projekt haben. Jedoch haben Sie die Möglichkeit die persönlichen Ergebnisse zu erhalten, falls Interesse besteht. Ebenfalls haben Sie die Möglichkeit die Kraft Ihrer Oberschenkelmuskulatur zu messen und eine neuartige Trainingsmethode auszuprobieren. Ein allgemeiner sozialer und wissenschaftlicher Nutzen geht aus diesem Projekt hervor, indem die gewonnen Erkenntnisse zur Entwicklung einer neuen, allenfalls besseren, Rehabilitationsmethode nach Kreuzbandrissen beitragen können.

6. Rechte
Sie nehmen freiwillig teil. Wenn Sie nicht mitmachen oder später Ihre Teilnahme zurückziehen wollen, müssen Sie dies nicht begründen. Sie dürfen jederzeit Fragen zur Teilnahme und zum Projekt stellen. Wenden Sie sich dazu bitte an die Person, die am Ende dieser Information genannt ist.

7. Pflichten
Als Teilnehmerin ist es notwendig, dass Sie
- sich an die notwendigen Vorgaben und Anforderungen durch die Projektleitung halten.
- die Projektleitung über Schmerzen oder andere Änderungen im Befinden informieren.
- sich frühzeitig melden, falls Ihre Teilnahme aufgrund einer Krankheit, Verletzung oder aus anderen Gründen nicht mehr möglich ist.

8. Risiken
Durch das Projekt sind Sie nur geringfügigen Risiken ausgesetzt. Folgende Faktoren sind möglich:
- Vorübergehende Rötung der Haut durch Sensoren/Tape, die während der Messung der verschiedenen Winkel verwendet werden
- Muskelkater nach den Messungen

Sollten Sie während dem Projekt schwanger werden, müssen Sie die Projektleitung sofort informieren und dürfen nicht weiter teilnehmen. Wenn Sie stillen, sind Sie von einer Teilnahme ausgeschlossen.

9. Ergebnisse
Die Projektleitung wird Sie während des Projekts über alle neuen Erkenntnisse informieren, die den Nutzen oder Ihre Sicherheit und somit Ihre Einwilligung zur Teilnahme beeinflussen können. Bei Zufallsbefunden, die bei Ihnen zur Verhinderung, Feststellung oder Behandlung bestehender oder künftig zu erwartenden Krankheiten beitragen können, werden Sie informiert. Wenn Sie nicht informiert werden wollen, sprechen Sie bitte mit der Projektleitung.

10. Vertraulichkeit von Daten und Proben
Für dieses Projekt werden Ihre persönlichen und medizinischen Daten erfasst. Nur sehr wenige Fachpersonen werden Ihre unverschlüsselten Daten sehen, und zwar ausschliesslich, um Aufgaben im Rahmen des Projekts zu erfüllen. Bei der Datenerhebung zu Studienzwecken werden die Daten verschlüsselt. Verschlüsselung bedeutet, dass alle Bezugsdaten, die Sie identifizieren

könnten (Name, Geburtsdatum), gelöscht und durch einen Schlüssel (Teilnehmercode) ersetzt werden. Die Schlüssel-Liste bleibt immer in der ZHAW. Diejenigen Personen, die den Schlüssel nicht kennen, können daher keine Rückschlüsse auf Ihre Person ziehen. Bei einer Publikation sind die zusammengefassten Daten daher auch nicht auf Sie als Einzelperson rückverfolgbar. Ihr Name taucht niemals im Internet oder einer Publikation auf. Manchmal gibt es die Vorgabe bei einer Zeitschrift zur Publikation, dass Einzel-Daten (sogenannte Roh-Daten) übermittelt werden müssen. Wenn Einzel-Daten übermittelt werden müssen, dann sind die Daten immer verschlüsselt und somit ebenfalls nicht zu Ihnen als Person rückverfolgbar. Alle Personen, die im Rahmen des Projekts Einsicht in Ihre Daten haben, unterliegen der Schweigepflicht. Die Vorgaben des Datenschutzes werden eingehalten und Sie als teilnehmende Person haben jederzeit das Recht auf Einsicht in Ihre Daten.

Es ist möglich, dass Ihre Daten für andere Untersuchungen zu einem späteren Zeitpunkt weiterverwendet werden oder später an eine andere Datenbank in der Schweiz oder ins Ausland für noch nicht näher definierte Untersuchungen versandt und verwendet werden. Diese andere Datenbank muss die gleichen Standards einhalten wie die Datenbank zu diesem Projekt. Für diese Weiterverwendung bitten wir Sie, ganz am Ende dieses Dokuments eine weitere Einwilligungserklärung zu unterzeichnen.

Möglicherweise wird dieses Projekt durch die Institution, die das Projekt veranlasst hat, überprüft. Der Projektleiter muss eventuell Ihre persönlichen und medizinischen Daten für solche Kontrollen offenlegen. Ebenso kann es sein, dass ausnahmsweise auch ein Vertreter der Versicherung Ihre Daten ansehen muss. Alle Personen müssen absolute Vertraulichkeit wahren. Wir halten alle Vorgaben des Datenschutzes ein und werden Ihren Namen weder in einer Publikation noch im Internet öffentlich machen.

11. Rücktritt
Sie können jederzeit aufhören und von dem Projekt zurücktreten, wenn Sie das wünschen. Die bis dahin erhobenen Daten werden gelöscht und nicht für die Analyse verwendet.

12. Entschädigung
Wenn Sie an diesem Projekt teilnehmen, bekommen Sie dafür keine Entschädigung. Es entstehen Ihnen keine projektspezifischen Kosten bei einer Teilnahme.

13. Haftung
Falls Sie durch das Projekt einen Schaden erleiden, haftet die Institution, die das Projekt veranlasst hat und für die Durchführung verantwortlich ist. Die Institution (ZHAW, Departement Gesundheit, Katharina-Sulzer-Platz 9, 8401 Winterthur) hat eine Versicherung abgeschlossen, um im Schadenfall für die Haftung aufkommen zu können. Die Voraussetzungen und das Vorgehen sind gesetzlich geregelt. Wenn Sie einen Schaden erlitten haben, so wenden Sie sich bitte an die Projektleitung.

14. Finanzierung
Das Projekt wird nicht durch Drittmittel finanziert.

15. Kontaktpersonen
Bei allen Unklarheiten, Befürchtungen oder Notfällen, die während des Projekts oder danach auftreten, können Sie sich jederzeit an eine dieser Kontaktpersonen wenden.
Leiterin am Studienort:
Dr. Eveline Graf
Zürcher Hochschule für Angewandte Wissenschaften
Katharina-Sulzer-Platz 9, Postfach
8401 Winterthur
+41 58 934 64 80
eveline.graf@zhaw.ch

Zürcher Hochschule für Angewandte Wissenschaften

zh aw Gesundheit

Mitarbeitende:
Michelle Haas
Zürcher Hochschule für Angewandte Wissenschaften
Katharina-Sulzer-Platz 9, Postfach
8400 Winterthur
+41 76 508 02 92
xhmc@zhaw.ch

Einwilligungserklärung

Schriftliche Einwilligungserklärung zur Teilnahme an einem Studienprojekt
Bitte lesen Sie dieses Formular sorgfältig durch. Bitte fragen Sie, wenn Sie etwas nicht verstehen oder wissen möchten.

Titel des Projekts:	Biomechanical Analysis of Selected Risk and Protective Factors for an Anterior Cruciate Ligament (Re-) Rupture during a Training with the ExerCube Biomechanische Analyse von ausgewählten Risiko- und Schutzfaktoren für einen Kreuzbandriss während eines Trainings mit dem ExerCube
verantwortliche Institution:	ZHAW - Zürcher Hochschule für Angewandte Wissenschaften Departement Gesundheit Katharina-Sulzer-Platz 9 8401 Winterthur
Ort der Durchführung:	Winterthur
Leiterin des Projekts am Studienort: **Mitarbeitende:**	Dr. Eveline Graf Michelle Haas
Teilnehmerin: Name und Vorname in Druckbuchstaben: Geburtsdatum:	______________________ ______________________

- Ich wurde von der unterzeichnenden Prüfperson mündlich und schriftlich über den Zweck, den Ablauf des Projekts, über mögliche Vor- und Nachteile sowie über eventuelle Risiken informiert.
- Ich nehme an diesem Projekt freiwillig teil und akzeptiere den Inhalt der zum oben genannten Projekt abgegebenen schriftlichen Information. Ich hatte genügend Zeit, meine Entscheidung zu treffen.
- Meine Fragen im Zusammenhang mit der Teilnahme an diesem Projekt sind mir beantwortet worden. Ich behalte die schriftliche Information und erhalte eine Kopie meiner schriftlichen Einwilligungserklärung.
- Ich bin einverstanden, dass die zuständigen Fachleute der Projektleitung und der für dieses Projekt zuständigen Ethikkommission zu Prüf- und Kontrollzwecken in meine unverschlüsselten Daten Einsicht nehmen dürfen, jedoch unter strikter Einhaltung der Vertraulichkeit.
- Bei Studienergebnissen oder Zufallsbefunden, die direkt meine Gesundheit betreffen, werde ich informiert. Wenn ich das nicht wünsche, informiere ich die Projektleitung.
- Ich kann jederzeit und ohne Angabe von Gründen von der Teilnahme zurücktreten, ohne dass ich deswegen Nachteile habe.
- Ich bin darüber informiert, dass eine Versicherung Schäden deckt, die auf das Forschungsprojekt zurückzuführen sind.
- Ich bin mir bewusst, dass die in der Teilnehmerinformation genannten Pflichten einzuhalten sind. Im Interesse meiner Gesundheit kann mich die Leiterin jederzeit ausschliessen.

Ort, Datum	Unterschrift Teilnehmerin

Bestätigung der Prüfperson: Hiermit bestätige ich, dass ich dieser Teilnehmerin Wesen, Bedeutung und Tragweite des Projekts erläutert habe. Ich versichere, alle im Zusammenhang mit diesem Projekt stehenden Verpflichtungen gemäss dem geltenden Recht zu erfüllen. Sollte ich zu irgendeinem Zeitpunkt während der Durchführung des Projekts von Aspekten erfahren, welche die Bereitschaft der Teilnehmerin zur Teilnahme an dem Projekt beeinflussen könnten, werde ich sie umgehend darüber informieren.

Ort, Datum	Name und Vorname der informierenden Prüfperson in Druckbuchstaben Unterschrift der Prüfperson

Zürcher Hochschule für Angewandte Wissenschaften
zh aw Gesundheit

Einwilligungserklärung für Weiterverwendung von Daten

Titel des Projekts:	Biomechanical Analysis of Selected Risk and Protective Factors for an Anterior Cruciate Ligament (Re-) Rupture during a Training with the ExerCube Biomechanische Analyse von ausgewählten Risiko- und Schutzfaktoren für einen Kreuzbandriss während eines Trainings mit dem ExerCube
Teilnehmerin: Name und Vorname in Druckbuchstaben: Geburtsdatum:	______ ______

Ich erlaube, dass meine Daten und Proben aus diesem Projekt in verschlüsselter Form für die medizinische Forschung weiterverwendet werden dürfen. Diese Einwilligung gilt unbegrenzt.

Ich entscheide freiwillig und kann diesen Entscheid zu jedem Zeitpunkt wieder zurücknehmen. Wenn ich zurücktrete, werden meine Daten anonymisiert. Ich informiere lediglich die Projektleitung und muss diesen Entscheid nicht begründen.

Ich habe verstanden, dass die Daten verschlüsselt sind und der Schüssel sicher aufbewahrt wird. Die Daten können im In- und Ausland an andere Datenbanken zur Analyse gesendet werden, wenn diese dieselben Standards wie in der Schweiz einhalten. Alle rechtlichen Vorgaben zum Datenschutz werden eingehalten.

Normalerweise werden alle Daten gesamthaft ausgewertet und die Ergebnisse zusammenfassend publiziert. Sollte sich ein für mich relevantes Ergebnis ergeben, ist es möglich, dass ich über die Projektleitung kontaktiert werde. Wenn ich das nicht wünsche, teile ich es der Projektleitung mit.

Wenn Ergebnisse aus den Daten und kommerzialisiert werden, habe ich keinen Anspruch auf Anteil an der kommerziellen Nutzung.

Ort, Datum	Unterschrift Teilnehmerin

Bestätigung der Prüfperson: Hiermit bestätige ich, dass ich dieser Teilnehmerin Wesen, Bedeutung und Tragweite der Weiterverwendung von Daten erläutert habe.

Ort, Datum	Name und Vorname der informierenden Prüfperson in Druckbuchstaben Unterschrift der Prüfperson

Appendix C: Questionnaire

Confidential

Fragebogen Personen- und Verletzungsbezogene Daten

Bitte füllen Sie den untenstehenden Fragebogen wahrheitsgemäss aus.

Vielen Dank!

Personenbezogene Daten	
Alter (in Jahren)	________________
Welche Sportart betreiben Sie?	○ Basketball ○ Fussball ○ Handball ○ Volleyball
Wie viele Stunden trainieren Sie pro Woche?	________________
Verhüten Sie hormonell?	○ Ja ○ Nein

Verletzungsbezogene Daten	
Haben Sie in den letzten 6 irgendeine Verletzung erlitten?	○ Ja ○ Nein
Bitte geben Sie jetzt alle Verletzungen, die Sie in den letzten 6 Monaten erlitten haben mit folgenden Informationen an: a. Diagnose --> Was haben Sie verletzt? b. Körperseite --> War die linke oder die rechte Körperseite betroffen? c. Wann haben Sie sich die Verletzung zugezogen?	__________________________

Appendix D: Placement of MTw Awinda Sensors

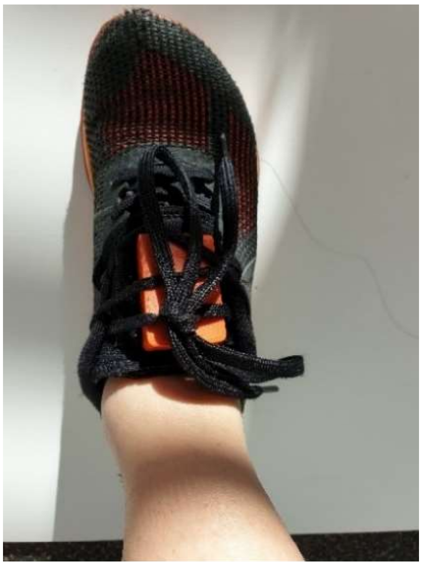

Figure 16: MTw Awinda right foot sensor placement in the middle on top of the foot (XSens Technologies, 2017).

Figure 17: MTw Awinda pelvis sensor placement flat on the sacrum (XSens Technologies, 2017).

Figure 18: MTw Awinda right lower leg sensor placement flat on the shin bone (XSens Technologies, 2017).

Figure 19: MTw Awinda right upper leg sensor placement on the lateral side above the knee (XSens Technologies, 2017).

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of Originality

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work:

Biomechanical Analysis of Selected Risk and Protective Factors for an Anterior Cruciate Ligament (Re-) Rupture during a Training with the ExerCube

Authored by: Haas, Michelle Christine

With my signature I confirm that

- I have committed none of the forms of plagiarism described in the 'Citation etiquette' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

I am aware that the work may be screened electronically for plagiarism.

Place, date	**Signature**