Motor learning in ACL injury prevention

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Discussion

Critical reflections

An ACL injury has widespread physical and psychosocial consequences for individual athletes because sports participation often is reduced,[6,7] as well as for society in terms of high healthcare costs.[55] Hence prevention of ACL injuries has received considerable attention over the last decades. Unfortunately, ACL injury prevention has not had long-term effectiveness as ACL injury rates have not decreased over the last decades.[2,38,88] One reason might be that the efficacy is highly dependent on the compliance of athletes and coaches.[35,47,71] Coaches are hesitant to implement ACL injury prevention exercises given the time investment and lack of performance benefits.[23,54,93,105] They may feel prevention training is 'too much', not of their primary interest,[30,40,47,53,61,99] does not offer a relative advantage over their existing practices, does not align with their needs or is too complex to implement in their setting.[72] However, having support from coaches and having a senior person in the hierarchy to influence the prevention program is extremely important.[26] These aspects should therefore be considered when implementing an ACL injury prevention program.[101] Lack of compliance from athletes is also a key factor as they state it "takes too long", "is boring", "has no performance benefits" or "is too difficult".[71]

Another reason for achieving suboptimal long-term results might be the way in which preventive training is taught. In the ACL injury prevention programs athletes are often encouraged to focus on the quality of their movements (e.g. knee-over-toe position), in order to improve awareness and knee control during cutting, jumping and landing.[1,43,57,70,71,75,78,83] While there may be intuitive reasons to give internal focus (IF) instructions, telling athletes explicitly how to move may be less suitable and even counterproductive for the acquisition of complex motor skills.[60] The transfer from learned movement techniques to unexpected and automatic movements during training or a game involves complicated motor control adaptations. Maintaining performance at a competitive level while trying to keep proper movement technique and performance seems warranted and provides a great challenge. This is imperative for training, clinical and research staff involved in ACL injury prevention in athletes. The advantages of applying external focus (EF) instructions or feedback have already been proven in golf putting,[91,113] basketball throwing[117] and volleyball[114] and tennis serving,[39] where athletes showed better learning effects when focusing on the goal of the movement (i.e. hole, basket, target at court). However, the integration of motor learning principles in widely accepted ACL injury prevention programs is not yet implemented in daily practice. The aim of this dissertation was therefore to contribute to the body of knowledge that may help to optimize ACL injury prevention programs through enhanced motor learning.

This is the first time the effects of different types of feedback on retention of learned motor skills in ACL injury prevention have been examined. Motor learning is defined as a relatively permanent change in a person's capability to perform a skill.[90] Retention and transfer tests performed after a certain time interval are used to allow any temporary performance-enhancing effects (such as caused by greater guidance) or performance-degrading effects (caused by increased fatigue) after practice to dissipate. Resulting in only the relatively permanent, or learned, effects being left. Another important aspect of retention and transfer tests is that all groups perform under the same conditions (e.g. without feedback or demonstrations). Then different groups can be equally compared, so that conclusions can be drawn about the effectiveness of different practice methods for learning.

As about 80% of the ACL injuries occur in non-contact situations,[51,74,88,106] optimization of movement technique itself is the goal. One part of the solution to injury prevention is grounded in the neuromechanics, that is the interaction of the brain and muscles to produce coordinated movements in different conditions. Since every brain and body in relation to the environment is different, the optimal solutions are also different and need to be individually tailored to athletes. In ACL injury prevention training an athlete is trained to maneuver, jump and land safely. A recent literature review on jump and landing technique shows that movement forms can be improved when EF of attention is used. This is illustrated by greater knee flexion angles, more center of mass (CoM) displacement, lower peak vertical ground reaction force (vGRF) and improved neuromuscular coordination, while maintaining or improving performance.[11] These findings are promising, as improved landing technique with increased jump performance yields an optimum between diminishing ACL injury risk without reduction in performance.

This dissertation started with an investigation of the clinical relevance of the sex differences during sidestep cutting. An overview of sex differences in sidestep cutting technique was presented in **Chapter 1**. Interestingly, even though the sex differences found during descriptive laboratory studies are being targeted in intervention studies, the effects have not been effectively transferred to the field; as no reduction of the ACL injury incidence is shown.[2,38,88] The commonly presented sex differences in biomechanical and neuromuscular profiles were systematically examined. As the kinematic and kinetic sex differences were of questionable clinical relevance and no quadriceps dominance (defined as an imbalance between knee extensor and flexor strength, recruitment, and coordination) was found in females, it was proposed that the approach of ACL injury prevention should target individual injury predisposition. A recent systematic review supported the findings of the current study.[80]

An EF of attention has many advantages compared to an IF of attention when learning motor skills. To substantiate this, a theoretical (**Chapter 2**) and practical (**Chapter 3**) framework was presented. These advantages especially seem to benefit athletes as skills acquired with an EF are more resilient under psychological,[10,37,66] and physiological fatigue,[59,84] while being more durable[5] and robust[98] when fast movements are required. The possibilities of applying this approach to ACL injury prevention were therefore investigated. Components of stress or fatigue can contribute to the eventual valgus collapse of the knee resulting in ACL injury. It is therefore quite relevant to teach movement skills that become permanent under all circumstances. Theoretically, this can have better long lasting effects and therefore aid in achieving long-term results. Individual assessment of landing technique to explore ACL injury risk factors will provide individual key components to target in interventions. Assisting athletes in finding optimal individual movement patterns and controlling forces belonging to complex motor skills is fundamentally different from teaching a 'one size fits all' movement pattern. For the control of complex tasks it is essential to address whole body kinematics, not only the lower extremity. Learning with an EF using video feedback of whole body movement could be an effective way to assist the athlete to reach a level in which performance is high, yet the chances of injury are low. The effect of immediate visual feedback of the athlete's own movement technique is an area that is still relatively unexplored. In order to fill the gap between the short-term positive results and the actual reduction of ACL injury rates, individualized feedback might enhance movement patterns better than instructing females 'to move like males' based on observed sex differences in descriptive studies.[64]

In Chapter 3 multiple practical examples are given on how to provide individual feedback. This can be accomplished by using video instructions and feedback with or without direct comparison with the expert,[24] with real-time feedback to improve movement technique,[9,32,62] or by stimulating implicit learning to find optimal solutions for each unique athlete. This type of learning gives the athletes the opportunity to view themselves performing the tasks correctly, making mistakes and responding to the corrections. Novel feedback techniques with an EF component for ACL injury prevention seems promising.

We wanted to better explore which factors contribute to proneness to ACL injury during landing in order to optimize interventions aimed at reducing risk for injury. It was presumed that better understanding of observed movement patterns would help to further optimize ACL injury prevention programs and therefore two experiments were conducted (Chapter 4 and 5). In these experiments we wanted to move beyond the descriptive phase and examine the effect of feedback on

movement strategies in both sexes. Therefore, we narrowed our focus in tackling the ACL injury phenomenon and examined how females and males respond to verbal and visual stimuli. For the techniques proposed in Chapter 3 to be successful, retention is one of the outcomes that should be examined to determine the learning effect. The two experiments included retention periods of one week and one month (Chapter 4) and one week (Chapter 5).

In **Chapter 4** the subjects performed unanticipated sidestep cutting as it is imperative to reduce knee joint loading during sport-specific tasks.[50,108] Subjects received video feedback of the individual's best trial: i.e. smallest knee frontal plane moment. The CoM position is essential to improve movement strategies.[15,34,42,44,49,89,92] The subjects also viewed the trunk as they were reviewing their own whole body technique and were instructed to replicate the trial to the best of their ability. In this experiment, visual feedback had a greater effect in males compared to females. Injury risk may have been reduced by an increase in knee flexion moment or decrease in knee valgus moment respectively, whereas performance (running speed) was not compromised. It is now known that females and males react differently and this should be examined further and incorporated into ACL injury prevention programs. The question arises whether a 'one size fits all' injury prevention program will work. Females may benefit more from a combination of individual visual and verbal cues. Given their physical capacities, males might be better able to adjust their limb mechanics during complex whole body dynamic actions to align the vGRF favorably and keep the chance of injury low due to their ability to use variability (Chapter 4).[22] The smaller ability in female athletes to actively control their landing is in accordance with a 'ligament dominant' landing.[68] Ligament dominant landing in females may be an important factor for increased injury risk, as they may be less able to attenuate high external forces. Whether less muscle strength is a result or cause of their ligament dominant landing style is still an issue of debate. It might be over-simplified that strengthening the quadriceps will result in improved movement patterns that reduce ACL injury risk.[14,65,69]

In addition, with reduced neuromuscular control, the direction of the vGRF is less controlled in all planes. Given the different response of females, researchers may need to consider that female athletes need more input or time to fully use the potential of plasticity of motor learning to adopt a safe landing strategy. In general, a combination of visual and verbal feedback strategies along with a combination of individualized visual feedback and feedback from an expert model seems to be promising.

Providing visual feedback via self-modeling (i.e. having yourself as an example to replicate) may be one method of modifying high risk movements. Males showed favorable results in terms of retention (Chapter 4). As feedback after good tri-

als enhances learning, this whole body approach where athletes can review their own technique might be promising. Experiencing competence through good trials, knowing that they are watching their best trial and being involved in analyzing own technique, adds to the evidence of motivational influences on motor learning: e.g. intrinsic motivation, interest and enjoyment, positive normative feedback.[21] In this study a predetermined feedback schedule was used. However self-controlled feedback schedules may have better potential.[19] If self-controlled feedback schedules are used, the athletes are more involved in their learning process, also considering that they mostly have quite a good sense of how they perform.[20] This so-called self-controlled practice has generally been assumed to initiate a more active involvement of the athlete, enhance motivation, increase the effort invested in practice[8,17,20,45] and increase compliance. Frontal plane knee moments were not statistically significantly reduced in this experiment. The most effective technique to reduce knee frontal plane moments during unanticipated sidestep cutting is still not known. Furthermore, the movement patterns of the female athletes were not affected significantly. It needs to be determined why females were not very responsive to the feedback modes used in the current study. The solution may be found in optimizing whole body technique,[15,25] by using combinations of instructions and feedback modes. Future research should examine how females respond to various combinations: visual and verbal feedback, expert and self-feedback and self-controlled learning. Females may need more time for their training to result in a safer landing pattern. In conclusion, the whole body approach through the use of video feedback in unanticipated sidestep cutting seems to be an effective approach to achieve permanent change, especially in males.

To further substantiate our theoretical model, the effect of expert video instruction and self-controlled feedback during drop vertical jumping was examined (**Chapter 5**). This study demonstrated beneficial effects of VI instruction in both female and male recreational athletes. Females also benefitted from verbal EF instructions. EF and VI instructions led to significant improvement in landing technique while maintaining performance (jump height) after a training session and remained present one week later. By showing the movement pattern of an expert, positive normative feedback was given, addressing good instead of poor trials. Addressing a positive movement goal is potentially more effective than correcting an athlete's faulty technique (e.g. "do not let your knee buckle inwards") as positive normative feedback enhances learning while negative normative feedback degrades learning.[18] In contrast to our experiment in Chapter 4, the subjects themselves determined when to receive feedback. Self-controlled feedback, i.e. providing feedback to the athletes on request with an overall score as an indication of their technique (the Landing Error Scoring System (LESS) score) led to signifi-

cant improvement in landing technique and performance after a training session and remained present one week later in the groups receiving verbal EF and expert video instructions. It is interesting to realize that most trainers and coaches determine if or when instructions or feedback will be provided.[86] However, considering the results of this study and others,[19,21] athletes should be able to control their own feedback schedule. To further strengthen the results of this study, biomechanical analysis should be added to exactly know the kinematic and kinetic improvements in technique. However, the LESS score is a validated clinical assessment tool that reveals individual movement patterns.[79] This allows training staff to assist athletes in practicing items with which an individual athlete still has room for improvement (e.g. knee flexion angle at initial contact).

In general, the experiments in Chapters 4 and 5 have some limitations. Even though retention was achieved in both studies, it is imperative for future studies to examine the transfer of effects to other tasks including on field performance. Since ACL injuries occur mostly in games during sidestep cutting or after landing from a jump, it is important to have athletes move safely during games. Only then can a valid judgement be made in respect to the value of the training for the trainers, coaches and athletes. In addition, the effect of combinations of feedback during these tasks, for example video feedback and IF instructions or video feedback and EF instructions, is still not known. This is important to examine as combinations of feedback modes could enhance learning, especially in complex tasks.[110] The specific type of focus that subjects will benefit most from is still unknown. The consistency with which subjects followed the prescribed attentional focus instructions was examined with a questionnaire in Chapter 5.[85] However, consciously writing down what a subject focused on during practicing may not yield an accurate report and reflect the automatic process that occurred during testing. Another issue pertains to the visual information provided, as subjects were only provided with posterior views. With complex maneuvers, more comprehensive feedback may be advantageous to achieve whole body technique modification as knee load is also dependent of trunk control.[44] Only a posterior view was provided, which may not give the athlete a complete understanding of what was required to move like the self (Chapter 4) or expert (Chapter 5) model. Offering different views (front, side, back) may have resulted in better adoption of the required technique. The instructions and feedback should be kept relatively simple though, as high complexity of feedback hampers motor learning.[58]

Lastly, risk factors for ACL injury in male athletes are relatively unknown.[3] Additionally, ACL injury mechanisms in male athletes have been sparsely investigated.[51,106] Even though motor control was enhanced in the male athletes after

they received video feedback, whether this reduced their ACL injury risk needs to be determined. ACL injury after sidestep cutting and landing from a jump also occurs in male athletes,[51] however, it is advised to collect more data and investigate whether these are the two most common injury mechanisms.

The results in Chapter 4 and 5 are in agreement with others showing that expert and/or self-video feedback improves movement technique.[25,67,76,77,81] The results of the performance measures (jump height and running speed) in Chapter 4, Chapter 5 and others[25] support the use of an EF attentional focus as opposed to an IF attentional focus.[67] Adding verbal instructions could enhance motor learning. However, the type of verbal instructions is important as instructions that induce an EF yield better results in motor skill acquisition and retention compared to IF instructions.[11,23,56,114]

Visual instructions can also affect landing technique when implemented in a home- or field-based program.[73,81,97] This is very promising as there is a need for unsupervised injury prevention programs.[31] Subsequently, athletes do not need constant monitoring during their prevention program, which in turn may solve the problem of coach compliance. A promising aspect of this study was that the effect remained over time, as also showed in Chapter 4 and 5 and another study.[81] In this dissertation, retention and transfer of learned motor skills are constant factors considered to be important to enhance ACL injury prevention programs. Based on Chapter 4 and 5, retention seems to be very promising when adapting an EF. The next step is to test the most optimal form of instructions and feedback in an on-field RCT intervention study to investigate the effect of attentional focus on transfer to the field in order to reduce the ACL injury incidence.

Conclusion

This dissertation supports the proposed theoretical framework of motor learning methods employing an EF that may optimize ACL injury prevention programs. Relatively permanent skill acquisition, shown with retention tests, was achieved with a relatively small number of training sessions. This highlights the economic potential to use various EF instruction modes. Less time is needed from staff to supervise training sessions. Low compliance from coaches may also become less of a problem as only periodic, not year long, training may be necessary. Moreover, the increase in performance may be the most important incentive for coaches to adopt the presented training programs as outlined in this dissertation.

Learning with an EF is an effective way to let the athlete optimize performance, yet keep the risk of injury low. This combination is a key element for effective ACL injury prevention. Practical tools for training staff are offered to implement this type of learning in their training regimens, like dyad training, video feedback or a simple change in wording to induce an EF of attention. A 'one size fits all' ACL injury prevention program while having females try to 'move like males' may not be optimal and it is concluded that risk factors should be determined and targeted on an individual basis. Athletes should be stimulated to find an individual way, including its effective variations, to tackle and reduce their risk factors for ACL injury. This dissertation only addressed a small percentage of all factors involved in ACL injury risk. However, the results of the experiments endorsed the theoretical framework (Chapter 2) and increased the body of knowledge on this topic. Insight was gained into the ACL injury paradigm and how enhanced motor learning can contribute to optimization of ACL injury prevention programs.

Future directions

The most challenging aspect for the future is to effectively implement the above suggested instructional and feedback strategies.[61,99] Further research is necessary to further strengthen and determine the most effective instruction and feedback modes, specifically for ACL injury prevention, in different sport populations (level, age, sex, healthy and ACL injured). Benefits of adopting an EF are not only seen relative to IF conditions, but also in comparison to control conditions.[112,115,116] Despite the obvious benefits, athletes have the tendency to adopt an IF even when they are not explicitly instructed to do so.[86] This is an interesting and under-exposed fact clinicians and coaches should be aware of. As coaches mostly use an IF (84.6%) while instructing their athletes, this indicates that coaches might not be familiar with the beneficial effects of using an EF.[86] It has been suggested that coaches view motor learning as too theoretically driven.[28] There is a need for better implementation and education materials for clinicians and training staff that highlights relevant motor learning issues.[95,109] Based on this dissertation and previous research[11,47] professionals are encouraged to use an EF to 1) increase the athlete's performance and 2) reduce the risk of ACL injury. So far, it has been stated that performance enhancement and injury risk reduction should be considered as two separate trainable capacities, as examined prevention programs did not enhance or even reduce performance.[23,54,93,105] Because performance enhancement is their main goal, it is very hard to convince coaches to implement an injury prevention program.[48,99] However, they should be taught that injury prevention and perfor-

mance improvement go hand in hand when adopting an EF of attention, as shown in our recent review[11] and Chapter 4 and 5 of this dissertation.

As the efficacy of ACL injury prevention programs is highly dependent on the compliance of athletes and coaches,[35,47,94,96] there is a need to further investigate how to make ACL injury prevention just 'part of the game'.[16] Knowledge and beliefs alone may not impact program adherence,[35,63] so other motivational factors must be considered along with the most effective way they can be targeted. Ideally, properly learned motor skills will become permanent.[90] Considering improved retention when an EF or visual feedback or instructions is applied (Chapter 4 and 5),[111] the newly learned skills need only periodic maintenance. This implies that less time from coaches and athletes will be needed to review and reinforce desired movement patterns. As this is less time consuming and enhances performance, compliance may increase.

Recent advances show that training staff is more and more in need of individual monitoring of athletes to prevent injuries,[16,61,100,102] enhance performance and improve safe return to sport. With new products using video feedback, 'exergaming' and 'gamified' scoring, common encountered barriers preventing training staff from implementing and adhering to the ACL injury prevention programs might be overcome. Literature is showing that these new products with gaming elements might enhance motivation and therefore compliance and effect.[12,104] Comparing one's own scores with oneself at home, an expert or teammates during practice and setting positive goals creates additional learning advantages due to social interaction and competition that enhance motivation.[36] Practicing with other athletes in an interactive manner may encourage athletes to set goals at a higher level of difficulty, as they will try to 'compete' with their peer.[52,107]

Injury prevention might also become more appealing with an innovative integrated approach where injury prevention, performance enhancement and rehabilitation are streamlined and facilitated.[103] This may help in reaching the goal that injury prevention in the future is just considered to be 'part of the game'.[16,61] Information can easily be up- and downloaded and will be readily available to the user wherever they need it. Most importantly, this approach might help coaches experiencing that injury prevention and performance enhancement are complementary to each other.

We recognize that an ACL injury is a result of many factors coming together, such as fatigue, physical fitness, age, prior injury, weather conditions or anatomy.[3,4,27] In this dissertation, it was postulated that the ACL injury mechanism is also a result of suboptimal motor control, opening a new area for research in ACL injury prevention. It should be noted that this outline of future directions is not strictly based on the experiments in this dissertation. However, the results in Chapter 4 and 5 point towards

a direction that confirms our presumption that concepts of motor learning have a great potential when implemented in ACL injury prevention. Program variables including the content, frequency and timing of feedback to improve the effectiveness of ACL injury prevention protocols must be further explored. Future on-field research should examine whether the innovative strategies mentioned and examined in this dissertation indeed provides more stable solutions in stressed and fatigued states,[87] i.e. game situations where the actual ACL injuries occur.

Implications: what's in it for athletes and their professionals?

From the athletes perspective, our proposed motor learning techniques may reduce time needed to reduce ACL injury risk. Coaches on the other side are less burdened in time allocated to ACL injury prevention as the proposed motor learning techniques enhance the learning process of skill acquisition. Compliance in adhering to preventative exercises and actual facilitation of behavioral change might be achieved when trainers and coaches realize the need and advantages of enhanced performance and reduce injury risk. Preventative exercises should be part of the regular training regimens where a better technique and performance is imperative for injury reduction. In addition, the benefits of intrinsic motivations' lower time requirement and motivating elements, such as having fun in setting goals and easy comparable scores with peer athletes, might increase chances for a successful integration of regular training regimens (Chapter 3).[48] As there is a wide variation of normal ranges across kinematic variables,[33] professionals working with athletes are encouraged to assist them in finding individual optimal movement patterns including effective variations while performing complex tasks. Athletes who have acquired motor skills with a large set of variations will most likely have decreased injury risk.[22,41,82] Trainers and coaches, sport physical therapists, athletic trainers, strength and conditioning specialists should consider sex specific capacities and preferences in learning styles as outlined in this dissertation. A combination of visual and externally focused verbal feedback strategies seems warranted, especially in regard to complex tasks (Chapter 4 and 5).[46] In addition, when individualized feedback along with expert instructions are offered and athletes have the ability to choose when to receive feedback, the learning effect seems most promising.[13,29]

In summary, clinical and training staff is encouraged to:

- add video instruction or feedback to their regular training regimens when teaching athletes technical skills
- add external focus verbal instruction or feedback to their daily training regimens when teaching athletes technical skills
- appreciate sex differences in learning styles, males seem to respond better to video feedback, females might need additional information
- consider providing combinations of instructions or feedback, especially with complex skills
- provide individual feedback based on individual movement patterns instead of applying a 'one size fits all' schedule
- alternate between providing self and expert videos as an example
- provide positive comparative feedback
- have their athletes practice with peers in for example dyad training
- have their athletes self determine when to receive feedback
- use simple instructions or feedback

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Summary

An ACL injury has profound physical and psychosocial consequences for athletes[4,5] as sports participation most often is reduced, as well as for society in terms of high costs for healthcare.[19] Hence prevention of ACL injuries has received considerable attention over the last decades. Implementation of a universal injury prevention program would save $100 per player per season and would reduce the incidence of ACL injury from 3.0% to 1.1% per season.[33] In general, the implementation of ACL injury prevention programs shows conflicting results,[30] and lacks long-term effectiveness with no reduction of ACL injury rates.[1,12,29] This suggests a missing link between improved movement technique in controlled settings and transfer of these learned techniques to the field or during a game.

One reason might be that efficacy is highly dependent on the compliance of athletes and coaches. Coaches are hesitant to implement ACL injury prevention exercises, given the time investment and lack of performance benefits.[9,18,32,36] They may feel it is too much, not of their primary interest,[10,13,15,17,22,35] does not offer a relative advantage over their existing practices, does not align with their needs or is too complex to implement in their setting.[26] Athletes, on the other hand, use arguments like it "takes too long", "is boring", "has no performance benefits" or "is too difficult".[25] Another reason for achieving suboptimal long-term results might be the way preventative training is given. In the current ACL injury prevention programs athletes are mostly encouraged to focus on the quality of their movements in order to improve awareness and knee control during cutting, jumping and landing.[14] However, telling athletes explicitly how to move may be counterproductive and less suitable for the acquisition of the control required for complex motor skills.[21]

The implementation of motor learning principles into ACL injury prevention programs has not been previously investigated. This innovative approach is further pursued in this dissertation. Motor skills can be learned with attention directed to the movement itself (e.g. "flex your knees"), which is defined as an internal focus (IF).[37] Whereas with an external focus (EF), attention is directed towards the effect of the movement (e.g. "imagine you are going to sit on a chair").[37] Employing instructions and feedback with an EF may enhance automatic movement control,[37] very relevant to training or game situations where unexpected and fast movements are required. In addition, improvement in the delivery of instructions and feedback to the athletes may enhance compliance, improve skill retention and its transfer to sport and optimize program efficiency, resulting in enhanced long-term outcomes.

The existing programs have yet to be effectively implemented and need to be sustainable over time in different conditions, for example using wide-spread implementation with high compliance rates and long-term retention.[31] It is therefore suggested that researchers focus on improving and universally implementing these

programs.[33] The aim of this dissertation was therefore to contribute to the body of knowledge that may help to optimize ACL injury prevention programs through enhanced motor learning.

In **Chapter 1** a systematic review is presented. As females have an increased risk for sustaining an ACL injury,[29] sex differences in ACL injury incidence play an important role in ACL-related research. We wanted to gain insight into these differences from a clinical point of view. Seven studies were included for this review to analyze the results of kinematic, kinetic and neuromuscular patterns during sidestep cutting maneuvers. Kinematic and kinetic sex differences were of questionable clinical relevance and quadriceps dominance (defined as an imbalance between knee extensor and flexor strength, recruitment, and coordination) was not found in females. The question arises whether ACL injuries during plant and cutting maneuvers are purely sex related and whether females have to learn to pivot and cut like males in order to reduce injury risk. The results suggest that future research should look beyond the isolated descriptive female/male comparison. It is important to examine the underlying causes and to question whether the biomechanical and neuromuscular differences really reflect the enhanced risk in females.[23] The descriptive studies give important insight, but cause-effect relationships are not well understood. Future research must focus on examining and understanding the causes underlying these differences in incidence and the best way to target this discrepancy. The largest number of ACL injuries still occur in male athletes.[29] If female and male athletes have their own risk factors,[2] different factors need to be considered when developing injury prevention programs tailored towards individual needs.

In **Chapter 2** we provide a theoretical framework from our search for optimizing current ACL injury prevention programs. The advantages of an EF compared to an IF especially seem to benefit athletes as skills acquired with an EF are more resilient under psychological[6,11,24] and physiological fatigue,[20,28] while being more durable[3] and robust[34] when fast movements are required. According to the 'constrained action hypothesis', a focus on the movement effect (i.e. EF) promotes the utilization of unconscious or automatic processes.[37] Whereas a focus on the movement itself (i.e. IF) results in a more conscious type of control that constrains the motor system and disrupts automatic control processes, as someone is focusing on his or her own body movements.[37] Learning with an EF, e.g. visual instruction or feedback, may enhance automatic movement control. For athletes it is very relevant and beneficial to learn movement skills that become permanent in all situations.

Optimization of the current prevention programs could be achieved by assisting athletes in finding optimal individual movement patterns by controlling forces

belonging to complex motor skills. This is fundamentally different compared to teaching a 'one size fits all' movement pattern. The effect of immediate visual feedback of the athlete's own movement technique is an area which is still relatively unexplored. Theoretically this can have better long lasting effects and therefore aid in achieving long-term results. In order to fill the gap between the short-term positive results and the actual reduction of ACL injury rates, individualized feedback might enhance movement patterns better than instructing females 'to move like males' based on observed sex differences in descriptive studies.[23]

Based on this theoretical framework, we continued by providing practical examples in **Chapter 3**. Adoption of instructions that induce an EF has important implications for ACL injury prevention as it potentially optimizes retention and transfer to the field. In addition, motor learning with an EF is effective for the establishment of safe movement technique with optimal performance (e.g. jump height).[7] Therefore, the development of novel feedback techniques with an EF component for ACL injury prevention seems promising. For example, this can be accomplished by using real-time, video feedback or dyad training with observation of oneself or a model, while adding positive, EF verbal feedback. Providing athletes individual visual feedback on movement technique allows them to view how they personally perform the movement task and actively problem solve by evaluating their trials and thus find individual ways to achieve optimal movement technique. Within this chapter we have proposed ideas for training staff to use in an attempt to advance ACL injury prevention.

Future research should focus on which, if any combinations of the presented novel techniques in Chapter 3 creates the least dependency on training staff as well as yields good retention and transfer to the field. For ACL injury prevention, it is imperative to reduce knee joint loading strategies during sport-specific tasks such as the complex maneuver of unanticipated sidestep cutting.[16] Therefore, the effect of novel feedback techniques on unanticipated sidestep cutting has been examined in **Chapter 4**. With this experiment we wanted to better understand the often observed phenomenon of sex differences in movement strategies and investigate how this can be addressed with proper interventions. The purpose of this study was therefore to investigate the effects of an IF (by a verbal stimulus) and an EF (by a visual stimulus) on peak knee joint loading during sidestep cutting over time in 90 female and male recreational basketball athletes. One session with feedback for the visual and verbal group was conducted, with two retention sessions (one week and one month after the first session) with no feedback for either of the groups. The largest effect was seen in the males receiving visual feedback, tending to reduce the frontal plane moments, while increasing the vertical ground reaction force (vGRF) and external knee flexion moment over time. Overall, females tended to keep their knee flexion moments low, potentially placing them at greater risk for

injury. Receiving visual feedback works advantageous in potentially reducing injury risk in males considering the increase in knee flexion moment and/or decrease in knee valgus moment, while performance (running speed) was not compromised. Learning new strategies can be hampered in females if they use their muscles less effectively. Perhaps, female athletes need more time to adopt a safe landing strategy. Moreover, it is plausible that females prefer different learning strategies (e.g. combination of visual and verbal feedback). The results of this study suggest that providing individual visual feedback to males may be one method of modifying sidestep movements, with promising results in terms of retention.

To further optimize novel feedback techniques, the last research project was conducted. The effect of attentional focus during a double legged drop vertical jump (DVJ) is investigated in **Chapter 5**. Self-controlled feedback along with providing expert videos was added to the protocol. The DVJ was evaluated with the real time Landing Error Scoring System (LESS). This practical tool gives an indication of injury risk to evaluate and optimize the DVJ landing technique.[27] Forty recreational athletes performed DVJ's in five sessions: a pretest (baseline measurement), two training blocks (TR1 and TR2), a posttest directly after TR1 and TR2 and a retention test one week later. General instructions were provided before the pretest, group specific instructions were offered before TR1 and TR2 started and after every 5 trials in TR1 and TR2. The IF group received instruction regarding attention to the body, the EF group received instruction directed to the movement effect and the video (VI) group viewed an expert video. In addition, subjects in the IF, EF and VI groups were free to ask for feedback after every DVJ in TR1 and TR2, which included their real time LESS score. Subjects were aware that a lower LESS score implied a better landing strategy. This study demonstrated beneficial effects of VI instruction in female and male athletes. Females also benefitted from verbal EF instructions. EF and VI instructions led to significant improvement in landing technique (while jump height was maintained) and remained present one week later. The fact that retention was achieved after a short training session has great potential to improve the effectiveness of current ACL injury prevention programs.

In summary, this dissertation contributed to the understanding of motor learning during complex tasks and an innovative approach in ACL injury prevention is presented. It is advised to consider sex specific EF feedback strategies when incorporating ACL injury prevention exercises. Professionals are advised to give instructions and feedback focusing on the result of the movement (EF) instead of specific body parts (IF) to 1) improve performance of the athlete (e.g. jump distance or jump height) and 2) decrease the risk of ACL injury. When training staff realize that injury prevention and performance enhancement go hand in hand, injury prevention can be viewed as 'part of the game'.[8,22]

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Samenvatting

Een voorste kruisband (VKB) blessure heeft verstrekkende fysieke en psychosociale consequenties voor sporters aangezien de sportparticipatie meestal moet worden verminderd,[4,5] alsook voor de maatschappij gezien de hoge gezondheidskosten.[19] Het is hierom dat VKB-blessure-preventie aanzienlijke aandacht heeft gekregen in de laatste decennia. De implementatie van een universeel preventieprogramma zou $100 per speler per seizoen schelen en zou de incidentie van het aantal VKB-blessures doen afnemen met 3.0% tot 1.1% per seizoen.[33] Over het algemeen laten de preventieprogramma's echter tegenstrijdige resultaten zien[30] en ontbreekt effectiviteit op de lange-termijn: geen afname van het aantal VKB-blessures.[1,12,29] Dit suggereert een 'missing link' tussen geleerde veilige bewegingstechnieken tijdens een gecontroleerde situatie zoals een training en de transfer hiervan naar het veld of tijdens een wedstrijd.

Een reden hiervoor kan zijn dat de efficiëntie in grote mate afhankelijk is van de compliantie van coaches en sporters. Coaches zijn vaak terughoudend met het implementeren van blessure-preventie-oefeningen gezien tijd die erin gestoken moet worden en het niet ervaren van een toename van de prestatie.[9,18,32,36] Ze hebben vaak het gevoel dat het te veel is, bovendien heeft het niet hun primaire interesse,[10,13,15,17,22,35] ze hebben niet het gevoel dat het hun voordeel oplevert ten opzichte van de huidige oefeningen, het komt het niet overeen met hun behoeften of is het te ingewikkeld om in de dagelijkse praktijk te integreren.[26] De sporters aan de andere kan geven aan dat het "te lang duurt", "het saai is", "het geen prestatievoordelen oplevert" of "het te moeilijk is".[25] De suboptimale lange-termijn resultaten kunnen anderzijds ook resultaat zijn van de manier waarop de preventieve oefeningen worden gegeven. In de huidige VKB-blessure-preventieprogramma's worden sporters vaak aangemoedigd om zich te focussen op de kwaliteit van hun bewegingen om zo bewustzijn en controle over de knie te vergroten tijdens het wenden, keren, springen en landen.[14] Echter, sporters expliciet vertellen hoe te bewegen lijkt juist contraproductief en minder geschikt voor het onder de knie krijgen van complexe motorische vaardigheden.[21]

Het implementeren van motorische leerprincipes in VKB-blessure-preventieprogramma's is tot dusver niet onderzocht. Deze innovatieve methode is nader onderzocht in dit proefschrift. Motorische vaardigheden kunnen worden aangeleerd met de aandacht gericht op de beweging zelf (bijvoorbeeld: "buig goed door je knieën"), ook wel interne focus (IF).[37] Bij een externe focus (EF) daarentegen is de aandacht gericht op de uitkomst of het effect van de beweging (bijvoorbeeld "ga op de stoel zitten").[37] Het geven van instructies en feedback met een EF kan de automatische controle van bewegingen verbeteren.[37] Dit is erg relevant tijdens een training of wedstrijd wanneer er onverwachte en snelle bewegingen vereist zijn. Bovendien kan een betere manier van het geven van instructies en feedback

aan de sporters de compliantie, retentie en transfer naar het veld verbeteren, om zo efficiëntie van het preventieprogramma te optimaliseren, resulterend in betere lange-termijn uitkomsten.

De bestaande programma's moeten nog op een effectieve manier geïmplementeerd worden en duurzaam worden over de tijd in verschillende condities (grootschalige implementatie met goede compliance en retentie op lange termijn).[31] Het advies is daarom dat onderzoekers zich richten op het verbeteren en implementeren van deze preventieprogramma's.[33] Het hoofddoel van dit proefschrift was om bij te dragen aan de 'body of knowledge' dat kan helpen om de huidige VKB-blessure preventie strategieën te verbeteren middels verbeterd motorisch leren.

In **Hoofdstuk 1** is een systematische review gepresenteerd. Aangezien vrouwen een hoger risico hebben op het krijgen van VKB-letsel,[29] speelt het onderzoeken van geslachtsverschillen een grote rol in VKB-gerelateerd onderzoek. We wilden inzicht krijgen in deze verschillen vanuit een klinisch perspectief. Om de resultaten van kinematische, kinetische en neuromusculaire patronen tijdens wendbewegingen te analyseren zijn 7 studies geïncludeerd. Kinematische en kinetische geslachtsverschillen toonden een twijfelachtige klinische relevantie en quadriceps dominantie (een disbalans tussen knie extensie en flexie kracht, rekrutering en coördinatie) werd niet gevonden bij vrouwen. De vraagt rijst nu of VKB-blessures tijdens wendbewegingen puur geslachtsgerelateerd zijn en of vrouwen wel moeten leren te wenden en keren zoals mannen om de kans op blessures te verlagen. Naar aanleiding van de resultaten is het advies dat er in toekomstig onderzoek verder moet worden gekeken dan de geïsoleerde beschrijvende man / vrouw vergelijking. Het is belangrijk om de onderliggende oorzaken kritisch te onderzoeken en na te gaan of de biomechanische en neuromusculaire geslachtsverschillen werkelijk het verhoogde risico bij de vrouwen reflecteren.[23] Deze beschrijvende studies verschaffen belangrijke inzichten, maar oorzaak-gevolg relaties worden er niet mee begrepen. Er moet aandacht worden besteed aan het onderzoeken en begrijpen van onderliggende oorzaken voor deze verschillen in incidentie en hoe deze aan te pakken. Het is belangrijk te beseffen dat mannen nog altijd voor het grootste aantal VKB-blessures zorgen.[29] Het is mogelijk dat elk geslacht zijn eigen risicofactoren heeft,[2] verschillende accenten moeten derhalve worden beschouwd bij het ontwikkelen van blessure preventie programma's, gericht op individuele behoeften.

In onze zoektocht naar het optimaliseren van de huidige VKB-blessure-preventieprogramma's hebben we een theoretisch raamwerk gepresenteerd in **Hoofdstuk 2**. Bij de voordelen van een EF vergeleken met een IF lijken met name ook sporters baat te hebben aangezien vaardigheden die met een EF verkregen zijn beter bestand zijn tegen psychologische[6,11,24] en fysiologische vermoeidheid,[20,28] en bovendien duurzamer zijn wanneer er snelle bewegingen vereist zijn.[3,34] Het is erg relevant om bewegingstechnieken aan te leren die beklijven in alle omstandigheden. Volgens de 'constrained action hypothesis', faciliteert een focus op het effect van de beweging (EF) onbewuste en automatische leerprocessen.[37] Terwijl een focus op de beweging zelf (IF) resulteert in een meer bewuste controle die het motorisch systeem beperkt en hiermee automatische processen verstoort, aangezien iemand zich dan op zijn eigen lichaamsbewegingen moet concentreren.[37]

Het optimaliseren van de huidige preventie-programma's kan worden bereikt door sporters bij te staan in het vinden van eigen optimale bewegingspatronen en het controleren van de krachten die bij complexe motorische vaardigheden horen. Dit is wezenlijk verschillend van het aanleren van een 'one size fits all' bewegingspatroon. Het effect van directe feedback op de eigen uitvoering van de sporter is nog relatief weinig onderzocht. Theoretisch gezien kan dit helpen in het behouden van resultaten op de lange-termijn. Om de kloof tussen de positieve korte-termijn-resultaten en de werkelijke reductie van het aantal VKB-blessure te slechten, kunnen geïndividualiseerde feedbacktechnieken efficiënter bewegingspatronen verbeteren dan het instrueren van vrouwen om 'zoals mannen te bewegen' gebaseerd op gevonden geslachtsverschillen tijdens beschrijvend onderzoek.[23]

Gebaseerd op dit theoretisch raamwerk, hebben we in **Hoofdstuk 3** praktische voorbeelden gegeven. Het aannemen van instructies die een EF teweegbrengen heeft belangrijke implicaties voor VKB-blessure-preventie aangezien het de retentie en de transfer naar de sport mogelijkerwijs kan verbeteren. Bovendien, motorisch leren met een EF is efficiënt voor het verkrijgen van een veilige bewegingstechniek in combinatie met een optimale prestatie (bijvoorbeeld spronghoogte).[7] Daarom is het ontwikkelen van nieuwe feedbackstrategieën met EF-componenten veelbelovend voor VKB-blessure-preventieprogramma's. Dit kan bijvoorbeeld bewerkstelligd worden met het gebruik van real-time, video feedback of dyad training met observatie van jezelf of een mede sporter als model, terwijl er positieve, EF verbale feedback door de begeleider wordt toegevoegd. Om VKB-blessure-preventie vooruit te helpen, hebben we in dit hoofdstuk ideeën voor trainingsstaf voorgesteld die zij kunnen toepassen tijdens hun trainingen.

Toekomstig onderzoek zou zich moeten richten op de vraag welke combinaties van de in Hoofdstuk 3 genoemde technieken, de minste afhankelijkheid van trainingsstaf creëren en toch een goede retentie en transfer naar het veld bevatten.

Voor de preventie van VKB-blessures is het belangrijk om de belasting op de knie te verminderen tijdens complexe sport-specifieke taken zoals het onverwacht wenden en keren.[16] Het effect van nieuwe feedbacktechnieken bij het wenden en keren is daarom onderzocht in **Hoofdstuk 4**. Met dit experiment wilden we het vaak geobserveerde fenomeen van geslachtsverschillen in bewegingsstrategieën beter leren begrijpen en onderzoeken hoe we dit met geschikte interventies aan kunnen pakken. Het doel van deze studie was om het effect van een IF (middels een verbale stimulus) en een EF (middels een visuele stimulus) op maximale kniebelasting te onderzoeken bij 90 vrouwelijke en mannelijke recreatieve basketballers. Er was een sessie met visuele of verbale feedback, met elk twee retentiesessies (1 week en 1 maand) zonder feedback voor elke groep. Het grootste effect werd gezien in de groep met mannen die visuele feedback kreeg. Zij reduceerden hun momenten in het frontale vlak, terwijl de verticale grondreactiekracht en het externe knieflexiemoment toenam en hoog bleef in de retentiesessies. Over het algemeen hadden de vrouwen de neiging hun externe knieflexiemomenten laag te houden. Dit plaatst hen echter mogelijk in een risicovollere positie. Het krijgen van visuele feedback lijkt voordelig in het potentieel reduceren van het blessurerisico bij mannen gezien de toename van het knieflexiemoment en/of afname van het knie valgus moment, terwijl de prestatie (rensnelheid) er niet onder leed. Het is aan de andere kant mogelijk dat het leren van nieuwe bewegingsstrategieën bij vrouwen gehinderd kan worden als zij hun spieren minder efficient gebruiken. Wellicht hebben vrouwen meer tijd nodig om een veilige landingsstrategie aan te leren. Bovendien is het aannemelijk dat vrouwen andere leerstrategieën prefereren (bijvoorbeeld een combinatie van visuele en verbale feedback). De resultaten wijzen er op dat het geven van individuele visuele feedback bij mannen een methode kan zijn om wendbewegingen aan te passen, met veelbelovende effecten ten aanzien van de retentie.

Om de nieuwe feedback-technieken verder te optimaliseren is het laatste experiment uitgevoerd. In **Hoofdstuk 5** is het effect van attentional focus onderzocht bij een double-legged vertical jump (DVJ). Er is self-controlled feedback toegevoegd tezamen met het laten zien van video's van experts. De DVJ werd geëvalueerd met het real time landing error scoring system (LESS). Dit is een praktische tool dat inzicht geeft in blessurerisico om zo DVJ landingstechnieken te evalueren en te optimaliseren.[27] Veertig recreatieve teamsporters voerden de DVJ uit in vijf sessies: een pretest (baseline meting), twee trainingsblokken (TR1 en TR2), een posttest direct na TR1 en TR2 en een retentietest één week later. Na een algemene instructie voorafgaand aan de test werden groepsspecifieke instructies gegeven vooraf aan TR1 en TR2. Dit werd tevens gedaan na elke vijf trials in TR1 en TR2. De IF groep ontving instructie gericht op het lichaam, de EF groep ontving instructie

gericht op de beweging en de video (VI) groep zag een instructievideo met een expert. Bovendien mochten de proefpersonen in de IF, EF en VI groepen feedback (de LESS score) vragen na elke DVJ in TR1 en TR2. Ze wisten alleen dat een lagere LESS score overeenkwam met een betere landingstechniek.

Deze studie liet voordelen van VI-instructie op landingstechniek bij de mannen en vrouwen zien. Vrouwen hadden ook baat bij verbale EF-instructies. EF- en VI-instructies leidden tot significante verbetering van de landingstechniek (terwijl spronghoogte gehandhaafd werd) en bleef aanwezig na een week. Het feit dat in beide studies retentie is bereikt na een korte trainingssessie heeft groot potentieel om de effectiviteit van de huidige VKB-blessure-preventieprogramma's te verbeteren.

Samenvattend, dit proefschrift heeft bijgedragen aan het begrijpen van motorisch leren bij complexe bewegingen en er is een innovatieve methode voor VKB-blessure preventie gepresenteerd. Geadviseerd wordt geslachtsspecifieke EF feedbackstrategieën in acht te nemen bij het implementeren van VKB-blessure-preventie-oefeningen. Professionals worden derhalve geadviseerd om instructies en feedback te richten op het resultaat van de beweging (EF, verbaal of visueel) in plaats van de manier waarop wordt bewogen (IF), om 1) de prestatie van de sporter te verbeteren (bijvoorbeeld spronghoogte of sprongafstand) en 2) het risico op VKB-blessures te reduceren. Als de trainingsstaf zich realiseert dat blessurepreventie en optimaliseren van prestatie hand in hand gaan kan dit helpen met het bereiken van het doel dat blessurepreventie in de toekomst gewoon beschouwd kan worden als 'part of the game'.[8,22]

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Anne
9 november, 2015

About the author

Anne Benjaminse

Anne Benjaminse was born on January 21, 1981 in Amersfoort, the Netherlands. Anne obtained her Bachelor's degree in Physical Therapy in 2004 from the School of Health Care Studies, Hanze University Groningen. After this, Anne started to specialize in sports medicine. In 2005-2006 she worked as a student researcher at the American Sports Medicine Institute in Birmingham, AL, USA. Anne earned her Master's degree in 2008 at the School of Health and Rehabilitation Sciences of the Department of Sports Medicine and Nutrition at the University of Pittsburgh, PA, USA. She worked as a graduate student researcher in the Neuromuscular Research Laboratory from 2006 to 2008. In 2008, Anne started her Phd study at the Center for Human Movement Sciences, University of Groningen. In addition, Anne works at the School of Sport Studies, Hanze University Groningen as coordinator, researcher and teacher since 2008. Her goal is to deliver a useful contribution to the field of sports medicine through innovative research, publications, presentations, interventions and teaching.

Peer reviewed publications

Shultz SJ, Schmitz RJ, **Benjaminse A**, Collins M, Ford K, Anthony S. Kulas AS. ACL Research Retreat VII: An Update on ACL Injury Risk Factor Identification, Screening and Prevention March 19th – 21st, 2015; Greensboro, NC. J Athl Train **2015** Accepted

Benjaminse A, Otten E, Gokeler A, Diercks RL, Lemmink KAPM, Motor Learning Strategies in Basketball Players and its Implications for ACL Injury Prevention: A Randomized Controlled Trial. Knee Surg Sports Traumatol Arthrosc **2015** Accepted

Dallinga JM, van der Does HTD, **Benjaminse A**, Lemmink KAPM. Dynamic postural stability differences between male and female players with and without ankle sprain. Phys Ther Sport **2015** Accepted

van der Does, HTD, Brink MS, **Benjaminse A**, Visscher C, Lemmink KAPM. Jump landing characteristics predict lower extremity injuries in indoor team sports. Int J Sports Med **2015** Accepted

Fleishman-Allison K, Sell TC, **Benjaminse A**, Lephart SM. Force sense of the knee is not affected by fatiguing the knee extensors and flexors. J Sport Rehab **2015** Accepted

Benjaminse A, Welling W, Otten E, Gokeler A. Novel methods of instruction in ACL injury prevention programs, a systematic review. Phys Ther Sport **2015**;16:176-186

Gokeler A, **Benjaminse A**, Welling W, Alferink M, Eppinga P, Otten E. The effects of attentional focus on jump performance and knee joint kinematics in patients after ACL reconstruction. Phys Ther Sport **2015**;16:114-120.

Benjaminse A, Gokeler A, Dowling AV, Faigenbaum A, Ford KR, Hewett TE, Onate JA, Otten E, Myer GD. Optimization of the anterior cruciate ligament injury prevention paradigm: novel feedback techniques to enhance motor learning and reduce injury risk. J Orthop Sports Phys Ther **2015**;45:170-182.

Gokeler A, Bisschop M, Myer GD, **Benjaminse A**, Dijkstra PU, van Keeken HG, van Raay JJ, Burgerhof JG, Otten E. Immersive virtual reality improves movement patterns in patients after ACL reconstruction: implications for enhanced criteria-based return-to-sport rehabilitation. Knee Surg Sports Traumatol Arthrosc **2014**

Gokeler A, Bisschop M, **Benjaminse A**, Myer GD, Eppinga P, Otten E. Quadriceps function following ACL reconstruction and rehabilitation: implications for optimisation of current practices. Knee Surg Sports Traumatol Arthrosc **2014**;22:1163-1174.

Gokeler A, Eppinga P, Dijkstra PU, Welling W, Padua, DA, Otten E, **Benjaminse A**. Effect of fatigue on landing performance assessed with the landing error scoring system (less) in patients after ACL reconstruction. A pilot study. Int J Sports Phys Ther **2014**;9:302-311.

Ter Stege MH, Dallinga JM, **Benjaminse A**, Lemmink KA. Effect of interventions on potential, modifiable risk factors for knee injury in team ball sports: a systematic review. Sports Med **2014**;44:1403-1426.

Gokeler A, **Benjaminse A**, Hewett TE, Ford KR, Paterno MV, Otten E, Myer GD. Feedback techniques to target functional deficits following anterior cruciate ligament reconstruction: implications for motor control and reduction of second injury risk. Sports Med **2013**;43:1065-1074.

Gokeler A, **Benjaminse A**, van Eck CF, Webster KE, Schot L, Otten E. Return of normal gait as an outcome measure in anterior cruciate ligament reconstructed patients. A systematic review. Intl J Sports Phys Ther **2013**;8:441-451

Shultz, SJ, Schmitz RJ, **Benjaminse A**, Chaudhari AM, Collins M, Padua DA. ACL Research Retreat VI: An Update on ACL Injury Risk and Prevention. March 22–24, 2012; Greensboro, NC. J Athl Train **2012**;47:591-603.

Dallinga JM, **Benjaminse A**, Lemmink KAPM. Which screening tools can predict injury to the lower extremities in team sports? A systematic review. Sports Med **2012**;42:791-815.

Gokeler A, **Benjaminse A**, Hewett TE, Lephart SM, Engebretsen L, Ageberg E, Engelhardt M. Arnold MP, Postema K, Otten E, Dijkstra PU. Proprioceptive deficits after ACL injury. Are they clinically relevant? A systematic review. Br J Sports Med **2012**;46:180-192.

Benjaminse A, Otten E. ACL injury prevention, more effective with a different way of motor learning ? Knee Surg Sports Traumatol Arthrosc **2011**;19:622-627.

Benjaminse A, Gokeler A, Fleisig GS, Sell TC, Otten E. What is the true evidence for gender related differences in ACL injury during plant and cut maneuvers? A systematic review. Knee Surg Sports Traumatol Arthrosc **2011**;19:42-54.

Benjaminse A, Lemmink KAPM, Diercks RL, Otten E. An investigation of motor learning during side-step cutting, design of a randomised controlled trial. BMC Musculoskeletal Disorders **2010**;13:235.

Benjaminse A, Sell TC, Abt JP, House AJ, Lephart SM. Reliability and Precision of Hip Proprioception Methods in Healthy Individuals. Clin J Sports Med **2009**;19:457-463.

Benjaminse A, Habu A, Sell TC, Abt JP, Fu FH, Myers JB, Lephart SM. Fatigue and sex differences during lower extremity kinematics of a single-leg stop-jump task. Knee Surg Sports Traumatol Arthrosc **2008**;16:400-407.

Benjaminse A, Gokeler A, van der Schans CP. Clinical Diagnosis of an Anterior Cruciate Ligament Rupture. A Meta-Analysis. J Orthop Sports Phys Ther **2006**; 36:267-288.

Invited publications

Benjaminse A. Sport Science Institute Groningen, Dutch Column. Blessures horen erbij? May **2015**

Interview: Groner, C. Internal vs external focus: Effects on motor learning. Lower Extremity Review. September **2014**

Benjaminse A. PhD Research: Preventing ACL injuries. Grasspoll, June **2010**

Benjaminse A, Gokeler A, Fleisig GS, Sell TC, Otten E. What is the true evidence for gender related differences in ACL injury during plant and cut maneuvers? A systematic review. Pittsburgh Orthopaedic Journal **2010**

Benjaminse A, Gokeler A, van der Schans CP. Klinische Diagnostiek van een Voorste Kruisband Ruptuur. Een Meta-Analyse. Stimulus **2007**

Benjaminse A, Gokeler A, van der Schans CP. Metaanalyse zu klinischen Tests: Klinische Diagnostik einer vorderen Kreuzband-Ruptur. Sportverletzung Sportschaden **2007**;21:108

Peer reviewed publications in preparation

Welling W, **Benjaminse A**, Gokeler A, Otten E. Enhanced Retention of Drop Vertical Jump Landing Strategies, A Randomized Controlled Trial. In revision Hum Mov Sci

Dallinga JM, **Benjaminse A**, Gokeler A, Otten E, Lemmink KAPM. Effect of an internally versus externally focused ACL injury prevention program on injury risk in female soccer players. Under review Int J Sports Med

Dallinga JM, **Benjaminse A**, Gokeler A, Cortes N, Otten E, Lemmink KAPM. Innovative video feedback on jump landing improves landing technique in males. Under review Int J Sports Med

Invited presentations

'OCON Sport Symposium: ACL injury, current concepts and future directions'. Prevention of ACL injury **Benjaminse A**. De Grolsch Veste. March **2015**. Enschede, the Netherlands

Jaarlijks FysioCongres Koninklijk Nederlands Genootschap voor Fysiotherapie (KNGF). Innovatie in de knierevalidatie. **Benjaminse A**, Gokeler A, Myer GD, Otten E. June **2014**. Maarssen, the Netherlands

15th European Society of Sports Traumatology Knee Surgery and Arthroscopy (ESSKA) Congress. Novel screening and individualized feedback techniques in ACL injury prevention to enhance retention and transfer. **Benjaminse A**, Gokeler A, Myer GD, Otten E. May **2014**. Amsterdam, the Netherlands

15th European Society of Sports Traumatology Knee Surgery and Arthroscopy (ESSKA) Congress. Motor Learning Rehabilitation Strategies after ACL Reconstruction in order to Return to Sport. Gokeler A, **Benjaminse A**, Padua DA, Welling W, Alferink M, Otten B. May **2014**. Amsterdam, the Netherlands

ALV Vereniging voor SportPsychologie in Nederland (VSPN). Relatie neuropsychologische factoren en landingstechniek. **Benjaminse A**. March **2014**. Hilversum, the Netherlands

7th Osnabrücker Symposium State of the Art in Orthopaedics, Traumatologie and Physical Therapy. Gokeler A, **Benjaminse A**, Padua D, Welling W, Alferink M, Otten E. Return to Sport Wissenschaft und Anwendung für die Praxis. March **2014**. Osnabrück, Germany

"PAPENDAL" symposium 2012 Physiology and Gender. **Benjaminse A**. Gender differences and sports. Dutch Association for Physiology. November **2012.** Amsterdam, the Netherlands

Deutsche Gesellschaft für Sportmedizin und Prävention (DGSP) Centenary Congress**.** Gokeler A, **Benjaminse A**, Myer G, Wulf G. Novel motor leaning to enhance movement patterns prior to return to sport after anterior cruciate ligament reconstruction. October **2012**. Berlin, Germany

5th Osnabrücker Symposium State of the Art in Orthopaedics, Traumatologie and Physical Therapy. Gokeler A, **Benjaminse A**, Otten E. Rehabilitation after ACL-reconstruction. March **2012**. Osnabrück, Germany

Nederlandse Orthopedische en Traumatologische Sportgeneeskunde (NOTS) meeting. **Benjaminse A**. Preventie van voorste kruisbandrupturen, screening en implementatie. Meander Medisch Centrum. February **2012**. Amersfoort, the Netherlands

Eerste Lijns Advies Noord Nederland (ELANN) Symposium State of the Art in ACL Reconstruction. **Benjaminse A**, Gokeler A. Motor learning in ACL injury prevention. December **2011**. Groningen, the Netherlands

Eerste Lijns Advies Noord Nederland (ELANN) Symposium State of the Art in ACL Reconstruction**.** Gokeler A, **Benjaminse A**, Otten E. New trends in ACL Rehabilitation. December **2011**. Groningen, the Netherlands

Intensive Program on Sport Performance: A Lifespan Challenge (IP-SPALC) **Benjaminse A**. From laboratory to field research: it's application in ACL injury prevention. May **2011**. Rome, Italy

9th Groningen Sports Medicine Symposium. Otten E, **Benjaminse A**, Gokeler A. Synthese van het onderzoek naar leren, cognitie en gedrag bij preventie en herstel na (knie) blessure. January **2011**. Groningen, the Netherlands

Symposium '30 years NAOG'. **Benjaminse A**, Sell TC. Workshop Neuromuscular training of the injured knee and shoulder. May **2010**. Utrecht, the Netherlands

Noordelijk Coach Platform (NoCP). **Benjaminse A**. Sportlab Measurements - Motion analysis with VICON. Hanze University, School of Sport Studies, October **2008**. Groningen, the Netherlands

Jubileumcongres Instituut voor Sportstudies: 'Kenniswerkers in beweging'. **Benjaminse A**. Sportlab Measurements - Motion analysis with VICON. Hanze University, School of Sport Studies, October **2008**. Groningen, the Netherlands

Coaches Workshop Mt. Lebanon High School District. **Benjaminse A**. Hands on demonstration for coaches, athletic trainers and teachers: ACL prevention program / warm up exercises. April **2008**. Mt. Lebanon, PA, USA

Weekly American Sports Medicine Institute (ASMI) Sports Medicine Conference. **Benjaminse A**. The Gender Bias: Biomechanical and Neuromuscular Differences in Athletic Tasks. A Critical Look at the Implications for ACL Injury and Prevention Programs. January **2006**. Birmingham, AL, USA

Annual Congress Koninklijk Nederlands Genootschap voor Fysiotherapie (KNGF). **Benjaminse A**, Gokeler A, van der Schans CP. Clinical Diagnosis of Anterior and Posterior Cruciate Ligament Rupture. A Meta-Analysis. November **2004**. The Hague, the Netherlands

Scientific Platform Presentations

Dallinga JM, **Benjaminse A**, Gokeler A, Cortes N, Otten E, Lemmink KAPM. Innovative feedback on jump-landing strategies improves landing technique in male team sport athletes. 20th Annual Congress of the European College of Sport Science (ECSS). June **2015**, Malmö, Sweden

Gokeler A, Welling W, Otten, E, **Benjaminse A**. Enhanced Retention of Drop Vertical Jump Landing Strategies Assessed with the Landing Error Scoring System. ACL Research Retreat VII. March **2015**. Greensboro, NC, USA

Benjaminse A, Otten B, Gokeler A, Diercks RL, Lemmink KAPM. Sex Specific Motor Learning Strategies: Implications for ACL Injury Prevention. ACL Research Retreat VII. March **2015**. Greensboro, NC, USA

Benjaminse A, Meijer M, Cortes N, Gokeler A. Relationship jump-landing technique and neuropsychological characteristics, implications for ACL injury prevention IOC World Conference on Prevention of Injury & Illness in Sport. April **2014**. Monte-Carlo, Monaco.

Dallinga JM, **Benjaminse A**, Gokeler A, Otten E, Lemmink KAPM. Effect of an internally versus externally focussed ACL injury prevention program on injury risk. IOC World Conference on Prevention of Injury & Illness in Sport. April **2014**. Monte-Carlo, Monaco.

Benjaminse A, Gokeler A, Leijten IAAM, Otten E. ACL Study Group Meeting. Invited Scientist Program. The effect of instruction on reducing peak vertical ground reaction force in recreational athletes. January **2014**. Cape Town, South Africa

Gokeler A, **Benjaminse A**, Welling W, Alferink M, Otten E. Effect of verbal feedback instructions on landing mechanics in patient after ACL reconstruction. ACL Study Group Meeting. January **2014**. Cape Town, South Africa

Dallinga JM, Does, HTD van der, **Benjaminse A**, Lemmink, KAPM. Relationship between neuropsychological performance and occurrence of knee injuries in team sports. 18th Annual Congress of the European College of Sport Science (ECSS). June **2013**. Barcelona, Spain

Benjaminse A, Gokeler A, Cortes N, Otten, E. Effects of stiff and soft landing techniques on knee loading during a single-leg cross-over hop. ACL Research Retreat VI. March **2012**. Greensboro, NC, USA

Cortes N, Greska E, Ambegaonkar JP, **Benjaminse A**, Onate JA. Landing Technique Affects Knee Position during a Pivot Task. ACL Research Retreat VI. March **2012.** Greensboro, NC, USA

Gokeler A, Bisschop MM, **Benjaminse A**, Arnold MP, Otten E. The quadriceps muscle weakness enigma after ACL-reconstruction. ACL Study Group Meeting. February **2012**. Jackson Hole, WY, USA

Benjaminse A, Gokeler A, Fleisig GS, Sell TC, Otten E. What is the true evidence for gender related differences in ACL injury during plant and cut maneuvers? A systematic review. 14th European Society of Sports Traumatology Knee Surgery and Arthroscopy (ESSKA) Congress. June **2010**. Oslo, Norway

Gokeler A, **Benjaminse A**, Ageberg E, Engebretsen L, Engelhardt M, Arnold MP, Postema K, Otten E, Dijkstra P. Proprioceptive Deficits after ACL-injury. Are They Clinically Relevant? A Systematic Review. ACL Study Group Meeting. February **2010**. Phuket, Thailand

Sell TC, **Benjaminse A**, House A, Huang HC, Abt JP, Lephart SM. A Lack of Peripheral Fatigue Effects on Force Sense at the Knee. American College of Sports Medicine (ACSM). May **2009**. Seattle, WA, USA

Sell TC, **Benjaminse A**, Nagai T, Nakagawa T, Abt JP, Lephart SM, Fu FH. Restoration of Sagittal and Transverse Plane Proprioception Following Double Bundle Anatomic ACL. International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports (ISAKOS) Congress. April **2009**. Osaka, Japan

Sell TC, **Benjaminse A**, Nagai T, House A, Nakagawa T, Abt JP, Lephart SM, Fu FH. Restoration of Sagittal and Transverse Plane Proprioception Following Double Bundle Anatomic ACL Reconstruction. American Academy of Orthopaedic Surgeons (AAOS). February **2009**. Las Vegas, NV, USA

Huang HC, Nagai T, Deluzio J, **Benjaminse A**, House AJ, Chu YC, Abt JP, Sell TC, Lephart SM. The Relationship among Body Composition, Anaerobic Power, Lactate Threshold and Maximal Oxygen Consumption in Male Soldiers. National Athletic Trainers' Association (NATA) Annual Meeting. June **2008**. St. Louis, MO, USA

Benjaminse A, Sell TC, House AJ, Huang HC, Abt JP, Lephart SM. The Effect of Fatigue on Force Sense of the Knee. 3rd South Eastern Meeting of the American Society of Biomechanics (SEASB). April **2008**. Birmingham, AL, USA

Benjaminse A, Gokeler A, van der Schans, C.P. Clinical Diagnosis of an Anterior Cruciate Ligament Rupture. A Meta-Analysis. 22nd Gesellschaft für Orthopädisch-Traumatologische Sportmedizin (GOTS) Annual Congress. June **2007**. Munich, Germany

Benjaminse A, Gokeler A, van der Schans CP. Clinical Diagnosis of an Anterior Cruciate Ligament Rupture. A Meta-Analysis. XVI International Congress on Sports Rehabilitation and Traumatology. April **2007**. Milan, Italy

Benjaminse A. Gender Differences in Knee Biomechanics in Athletic Tasks. A Critical Look at the Implications for ACL Injury. 1st South Eastern Meeting of the American Society of Biomechanics (SEASB). March **2006**. Atlanta, GA, USA

Awards

Best Poster Price. 11th Groningen Sports Medicine Symposium.van der Does H. Dallinga JM, **Benjaminse A**, Brink MS, Visscher C, Lemmink KAPM. Dynamic ankle stability and ankle sprain occurrence in elite ball team athletes: a one season prospective study. January **2013**. Groningen, the Netherlands.

Student honoree of the 32nd Annual Honors Convocation of the University of Pittsburgh. February **2008**. Pittsburgh, PA, USA

Research Development Fund, University of Pittsburgh, School of Health and Rehabilitation Sciences. $1000.00. **Benjaminse A**, Sell TC, Abt JP, House AJ, Lephart SM. Reliability and Precision of Hip Proprioception Methods in Healthy Individuals. November 2007. Pittsburgh, PA, USA

Fu Graduate Research Award, 2007 $1500.00. **Benjaminse A**, Sell TC, Abt JP, House AJ, Lephart SM. Freddie H. Reliability and Precision of Hip Proprioception Methods in Healthy Individuals. May **2007**. Pittsburgh, PA, USA

Best Presentation Award. Southeastern Meeting of the American Society of Biomechanics Georgia Tech University, Georgia Institute of Technology, School of Applied Physiology. Presentation: Gender Differences in Knee Biomechanics in Athletic Tasks. A Critical Look at the Implications for ACL Injury. April **2006**. Atlanta, GA, USA

Student Research Award. Second Place. Received at Annual Congress of Koninklijk Nederlands Genootschap voor Fysiotherapie. (KNGF). November **2004**. The Hague, the Netherlands

Editorial service

Manuscript Reviewer American Journal Sports Medicine
Manuscript Reviewer British Journal Sports Medicine
Manuscript Reviewer Clinical Biomechanics
Manuscript Reviewer Gait & Posture
Manuscript Reviewer Journal of Applied Biomechanics
Manuscript Reviewer Journal of Athletic Training
Manuscript Reviewer Journal of Science and Medicine in Sport
Manuscript Reviewer Journal of Sport Rehabilitation
Manuscript Reviewer Journal of Orthopaedic and Sports Physical Therapy
Manuscript Reviewer Journal of Visualized Experiments
Manuscript Reviewer Knee Surgery Sports Traumatology Arthroscopy
Manuscript Reviewer Medicine & Science in Sports & Exercise
Manuscript Reviewer Physical Therapy in Sport
Manuscript Reviewer Sports Health
Manuscript Reviewer Sports Medicine

Previous SHARE dissertations

2015

Feijen-de Jong, EI.
On the use and determinants of prenatal healthcare services
(prof SA Reijneveld, prof F Schellevis, dr DEMC Jansen, dr F Baarveld)

Sulkers, E.
Psychological adaptation to childhood cancer
(prof R Sanderman, prof PF Roodbol, prof ESJM de Bont, dr J Fleer, dr WJE Tissing)

2014

Troquete, NAC.
START-ing risk assessment and shared care planning in out-patient forensic psychiatry; results from a cluster randomized controlled trial
(prof D Wiersma, prof RA Schoevers, dr RHS van den Brink)

Golea, E.
Functioning of young individuals with upper limb reduction deficiencies
(prof CK van der Sluis, dr RM Bongers, dr HA Reinders-Messelink)

Brinksma, A.
Nutritional status in children with cancer
(prof PF Roodbol, prof R Sanderman, prof ESJM de Bont, dr WJE Tissing)

Eriks-Hoogland, IE.
Shoulder impairment in persons with a spinal cord injury & associations with activities and participation
(prof LHV van der Woude, porf G Stucki, prof MWM Post, dr S de Groot)

Dontje, ML.
Daily physical activity in patients with a chronic disease
(prof CP van der Schans, prof RP Stolk)

Bredeweg, S.
Running related injuries
(prof JHB Geertzen, dr J Zwerver)

2013

Bosker, BH.
Pitfalls in traditional and innovative hip replacement surgery
(prof SK Bulstra, dr CCPM Verheyen, dr HB Ettema)

Sobhani, S.
Rocker shoes for ankle and foot overuse injuries: a biomechanical and physiological evaluation
(prof K Postema, prof ER van den Heuvel)

2011

Reininga, IHF.
Computer-navigated minimally invasive total hip arthroplasty; effectiveness, clinical outcome and gait performance
(prof SK Bulstra, prof JW Groothoff, dr M Stevens, dr W Zijlstra)

2010

Zwerver, J.
Patellar tendinopathy; prevalence, ESWT treatment and evaluation
(prof RL Diercks, dr I van den Akker-Scheek, dr F Hartgens)

van Ittersum, MW.
Chronic musculoskeletal disorders assessment and intervention
(prof JW Groothoff, prof CP van der Schans, dr CP van Wilgen, dr MF Reneman)

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