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SUMMARY AND GENERAL DISCUSSION

Injury prevention in team sport athletes

Joan Dallinga
SUMMARY

The risk of getting injured in team sports is considerably high, especially in the lower extremity. Considering the physical and psychological consequences of injuries in team sports combined with large costs, the prevention of these injuries is crucial. Coaches and athletes are often hesitant to implement an injury prevention program, because of the time and effort needed. They think it is difficult to integrate, it is not their primary interest, the benefits are not clear, it lacks sport-specificity and the injury prevention programs do not translate to real-life situations. The aim of this thesis was to increase our knowledge about the role of injury screening tools and prevention programs for lower extremity injuries. Hereby we offer potential solutions for above mentioned issues and contribute to further implementation of injury screening tools and prevention programs.

Central to the first part of this thesis were injury screening tools. A list of simple, easy-to-use and implement screening tools that do not require extensive and expensive materials could assist in showing that screening tools can be applied in practice and can be implemented on a small and large scale. Therefore, in Chapter 2 a systematic review is presented where the predictive values of anthropometrics and physical screening tests for injuries to the leg in general, anterior cruciate ligament (ACL), knee, hamstring, groin and ankle in team sports are described. Twenty-three studies were included in this review. A wide range of screening tools were described including balance, strength, laxity and flexibility (range of motion (RoM)) tests. Anthropometric tests for measuring body mass index, age and body height were found as well. Studies agreed about predictive ability of some of these measures (e.g. postural sway and greater strength of the plantar flexors for ankle injuries), whereas there was debate about predictive value of other measures (e.g. hamstring flexibility and hamstring/quadriceps ratio (H : Q) for hamstring injury).

Age, sex, sport, and level of athletes varied in these studies. Most studies examined the predictive value of one type of screening tool, while some studies performed multi-variate analyses. Important to note is that only half of included studies described confounders that may have interfered with the results, such as age, sex, previous injuries and exposure time. Moreover, studies examining ACL injury screening tools were mainly directed at female athletes, while in absolute terms males experience more ACL injuries. In addition to the report on valid screening tools, we described the reliability of some promising screening tools as well, of which the predictive value has yet to be determined. For example, the landing error scoring system (LESS) and 2-dimensional video analysis, both ACL injury screening tools,
Chapter 7 showed good reliability. In addition, reliable, potential screening measures for ankle sprains were generalized joint laxity, ankle ligamentous stability and ankle strength. The ability of these tests to predict injury has yet to be examined.

Although postural stability or balance tests can predict the occurrence of ankle sprains (Chapter 2), these tests included static balance tasks that were not sport-specific. Consequently, in Chapter 3 the potential of the dynamic stability index (DSI) to discriminate between athletes who sustained an ankle sprain and athletes who did not was determined as well as the potential of the DSI to discriminate between athletes who had a history of ankle sprain and athletes who did not. In addition, sex differences in the DSI were analyzed. DSI was measured during a single-leg hop-stabilization task in male and female volleyball, basketball and korfball athletes prior to the start of the season. During the season, ankle sprains were reported. The most important finding was that male korfball, basketball and volleyball athletes showed higher DSI scores than their female counterparts. Which means that males performed worse on the dynamic stability test. The second finding was that no significant differences in DSI were found between athletes with a previous ankle sprain and athletes without a previous ankle sprain. In addition, preseason DSI scores in athletes who sustained an ankle sprain in the season after the screening, did not differ from athletes without an ankle sprain. Still, athletes who sprained their ankle reported a trend towards higher DSI scores. Further research should be undertaken to investigate the potential of the DSI in predicting ankle sprains.

The following three chapters, i.e. Chapter 4, 5, and 6, focused on ACL injury prevention programs. In Chapter 4 an overview of literature was provided regarding the effect of interventions on modifiable, potential risk factors for knee injuries in team ball sports. Results showed that there are several interventions that can change risk factors for knee injuries. Short programs are recommended (maximal 25 minutes) in order to increase adherence. Neuromuscular training, including plyometric and agility exercises combined with verbal or video feedback, was the most powerful component for reducing knee valgus. Furthermore, neuromuscular control training including plyometric and resistance exercises with augmented feedback is recommended for improving knee flexion angles and moments. Isolated hamstring resistance exercise was the best component to improve the H : Q ratio. Moreover, neuromuscular training programs may increase hamstring activity. Overall, this review showed that in order to be effective the exercises in a knee injury prevention program should be specific to the task that needs to be improved. A limited number of studies focused on male athletes. As a large amount of ACL injuries are reported
in males, determining which interventions can improve knee injury risk factors in male athletes is an important issue for future research.

Instructions in injury prevention programs can be given to induce an internal attention focus (IF) or external attention focus (EF). EF instructions encourage automatic learning processes and thereby may improve the translation of learned movements during training to performing that task during competition.\textsuperscript{10,11} Therefore, in \textbf{Chapter 5} the feasibility and effects of an IF and an EF ACL injury prevention program integrated in a warmup for female soccer athletes were assessed. The effect of adopting an EF versus IF in an ACL injury prevention program on biomechanical ACL injury risk factors during a drop vertical jump (DVJ) was analyzed. Individual scores were calculated for all athletes. Jump-landing kinematics and kinetics of hip, knee and ankle were collected. Results showed a significant greater adherence for the EF group compared to the IF group. With regard to landing technique, in both groups some of the athletes improved their landing technique and some athletes did not. For instance, peak knee valgus moment decreased for three athletes (of nine athletes) in the IF group, whereas in the EF group peak knee valgus moment decreased slightly for six athletes (out of 11 athletes). No statistical analysis was performed, therefore no conclusions can be made about which program had the largest effect on landing technique. This was the first study implementing EF instructions on the field. Based on the findings and influence of practical issues, additional experiments are needed to further optimize the warmup program including EF instructions.

Lastly, based on the latest scientific ideas considering ACL injury prevention and motor learning, a video feedback tool was developed, called Vizmo. Motor learning focuses on the process of learning motor skills with a relatively permanent change.\textsuperscript{12} This innovative tool is unique because of its ability to present two movies (expert and self) at the same time. Two videos (expert and athlete) were time synchronized and an overlay of body contours performing a DVJ landing task is presented. Using this technique, the expert model forms a target movement pattern for the athlete. The objectives of \textbf{Chapter 6} were (1) to analyze the effect of video feedback with overlay method on overlap of athlete and expert contours in male and female soccer, basketball, handball and korfball athletes during training sessions while performing a DVJ and (2) to determine the effect of the video feedback with overlay method on DVJ landing strategies in male and female team sport athletes. Hip, knee and ankle kinematics and kinetics of the DVJ was collected during pre- and posttest. In addition, the percentage overlap of expert and athlete contours during the DVJ was collected. This percentage allowed us to examine the learning process during the intervention.
As a main result of the video feedback, the hip flexion angle and hip RoM increased while ankle dorsiflexion moment, ankle dorsiflexion angle and vertical ground reaction force (vGRF) decreased for the males in the video feedback (VI) group when compared to the control (CTRL) group. At posttest, a lower vGRF and ankle dorsiflexion moment was maintained for the males in the VI group compared to the males in the CTRL group. These changes in landing technique for males in the VI group were supported by an improved expert and athlete overlap during the training sessions. No changes in knee valgus moment, knee flexion angle and knee RoM were found after the training sessions. Although females in the VI group increased the percentage overlap during the sessions, this increase was smaller than in males and no significant change in landing kinematics or kinetics was found. This study showed that by providing video feedback with the overlay method, male athletes can improve DVJ landing technique. Further, it could be suggested that female athletes may need additional (verbal) feedback to improve their landing technique. The current findings add to a growing body of literature on potential of video feedback in correcting faulty landing patterns.

In summary, this thesis has contributed to the knowledge of injury screening tests and prevention programs for lower extremity injuries. We found several screening tools to screen for lower extremity injury risk. Current screening tools may need to be further investigated in regard to predictive value, practical applicability and sport-specificity. In addition, new methods were introduced that can improve current ACL injury prevention programs. EF instructions and video feedback were used to encourage automatic learning processes. These methods need to be further optimized and evaluated. However, visual feedback seems promising in optimizing landing technique. This thesis adds to the growing body of knowledge on benefits of EF feedback in ACL injury prevention.

**CRITICAL REFLECTIONS**

**Screening tools**

*Predictability versus applicability*

In Chapter 2, several (potential) predictive screening tests were described (step 2, TRIPP). These screening tests were divided into anthropometrics, flexibility tests, balance tests, strength tests and ACL injury screening tools. Anthropometric, flexibility and some of the balance screening tools (e.g. single leg balance (SLB) test)
are easy to use in the field. In contrast, if coaches want to implement screening tools such as ACL injury screening tools, strength and other balance screening tools (such as measuring postural sway with the NeuroCom New Balance Master), they often need expensive equipment or depend on availability of motion analysis labs in their surroundings. Particularly for recreational level coaches, this could deter them from screening their athletes.

Based on Chapter 2, it seems that a controversy may exist between predictability of the described measures and the practical applicability of the ACL injury screening tests. The generalizability of these predictive measures to the field may be limited due to high costs of equipment limiting the applicability on a large scale. These results match with those reported in previous studies. Furthermore, these screening tests still need to be validated in different populations. Subsequently, the effect of screening with these tools combined with an injury prevention program needs to be determined. The same is true for balance screening tests as a predictive relationship was found in only one population.

On the other hand, simple and low-cost screening methods have been introduced and seem promising (Chapter 2). Although the practical applicability of these tests may be better, the predictive value of these screening tools is yet unknown. In regards to ACL injury screening, an example of a simple and low-cost screening method is the real-time observational screening test of knee valgus during landing, which demonstrated good reliability. Two other examples are two-dimensional video analysis of frontal-plane dynamic knee valgus and a real-time LESS score. The LESS and 2-dimensional video analysis showed good reliability and may be suggested as potential screening tools for ACL injury. To date, the LESS has only shown predictive value in young female soccer athletes, but not in an adult population of team sport athletes. Recently an iPad app for the LESS was developed, which may also provide an easy tool to evaluate landing technique. Currently, there is a lack of ACL injury screening tests that are predictive as well as applicable in practice.

In line with the results of this thesis, a recent meta-analysis by Swart et al. concluded that screening for athletes at risk for ACL injury is currently not cost-effective. The expensive materials needed for screening athletes at risk for ACL injury, for instance the Vicon Motion Analysis System, limit the possibility to measure large groups of athletes. It would be more effective not to screen athletes and provide the injury prevention program to all athletes. This observation is supported by recently published reviews on screening tests for ACL injuries. These reviews examined field-based screening tests, in vivo biomechanical risk factors and neuromuscular markers predictive for ACL injuries. It seems that there is little evidence for
neuromuscular markers and in vivo biomechanical risk factors being predictive of ACL injuries. Further, there is little evidence to support the predictive validity of field-based screening methods in identifying ACL injuries in a range of populations.\textsuperscript{14,15}

**Sport-specificity**

Another important question is whether screening methods provide information in a sport-specific context. Do they involve tasks that athletes execute or situations that athletes are in while performing their sport? For instance, ACL injury risk is often measured during jump-landing and side-step cutting.\textsuperscript{27,28} These movements are high-risk movements that are often performed in basketball, volleyball and soccer. For ACL injury screening tools, it seems that validity of measuring injury risk during sport-specific movements was limited.\textsuperscript{15} Isolated landings in a controlled lab situation are not the same as movements performed during sport practice or competition. During team training, the player has to visually perceive the constantly and quickly changing, unpredictable environment (e.g. movement of another player, opponent or a ball), quickly process these situational-specific visual-spatial cues within the central nervous system and develop an appropriate physical response while maintaining dynamic stability of the body. Several studies have shown that experimentally visually cued temporal constraints can affect whole body kinematics and knee loading during athletic activities such as cutting.\textsuperscript{29,30}

Chapter 2 showed that there are some simple screening tests for balance and some tests that require expensive materials. The simple balance tests may be easy to apply in large groups of athletes, however they are limited in their sport-specificity. In regards to ankle sprains, it would be more specific to measure postural sway during a landing task.\textsuperscript{31,32} Therefore, in Chapter 3, the potential of the DSI as screening test for ankle sprains was determined. However, no significant altered preseason DSI during a single-leg hop-stabilization task was found in athletes who sprained their ankle. Although not significant, all DSI subscales except one were higher for athletes who sustained an ankle sprain and moderate to strong effect sizes were reported. The single-leg hop-stabilization task is more challenging and dynamic than a static single leg balance task, however it could be that this task still does not match with motor tasks executed in a real sports setting. A second option to make this test more sport-specific may be to simulate sport-specific situations.\textsuperscript{33} Current screening tools for lower extremity injuries could further be improved in regards to their practical use and sport-specificity. We suggest that sport-specificity be further enhanced by
testing the athletes while they are in a fatigue state, by adding decision tasks or by including opponents.34-37

**ACL injury prevention programs (step 3 & 4, TRIPP)**

*Implementing external focus instructions in a real-sport situation*

To the best knowledge of the authors, the study reported in Chapter 5 is the first to incorporate an EF in an on-field injury prevention warmup program. In this study, the implementation context was taken into account. A few studies have evaluated EF instructions in ACL injury prevention programs in a lab setting. Positive effects of an EF on core position and control movement strategy (Core-PAC) warmup were demonstrated.38 Two other studies by our research group have reported positive effects of instructions with an EF or visual feedback for a side-step cutting maneuver and a DVJ in a lab.39,40 Furthermore, one study showed an increased center of mass (CoM) displacement and larger sagittal joint moments during a jump and reach task when EF instructions were provided.41 These studies showed that an EF might work in a laboratory setting. However, when EF instructions are used in a practice situation several confounding factors need to be taken into account.

One example is adapting the EF instructions in order to increase suitability for practice. Our experience was that the EF instructions for plyometric and strength exercises were easier to understand compared to the EF instructions directed at trunk control and warmup exercises (e.g. jogging and backwards running). These warmup exercises were performed at the start of the warmup. We suggest that in a future study, EF instructions for trunk control and warmup exercises need to be revised. It is crucial to take the athlete’s opinion into account in further developing EF instructions for ACL injury prevention programs, as suggested by Donaldson et al.42 Coaches and trainers could assist in providing clear EF instructions. Insight into the implementation context could provide relevant input for improving implementation in real sports situations (step 6, TRIPP).43

**Duration**

In recent studies the challenge of implementing an ACL injury prevention program in practice was raised. Studies that analyzed neuromuscular training interventions for ACL injury reduction reported that feasibility and implementation were major limitations.44-46 For instance, duration of the injury prevention program may influence implementation. The program should not require a lot of time from the training sessions or expensive materials/equipment.47 Based on our review in Chapter 4,
a maximum of 25 minutes per training session was advised. However, this is still quite long, especially for recreational coaches and athletes who usually practice 1-2 times per week and may decrease adherence to the program. A review by O’Brien and Finch,\textsuperscript{48} reported that the necessity of data collection and duration of the program were the most important barriers described by coaches to adopting an injury prevention program. Coaches and athletes indicated that the duration of 20 minutes for the warmup program evaluated in Chapter 5 took too much time. In terms of duration, the results of Chapter 6 seem promising, only two 15 minute sessions of with video feedback were needed to change landing pattern in males one week after the training sessions. Potentially, this could imply that little time investment is required from medical and training staff. However, long-term results of the video feedback with overlay method need to be examined before we can provide recommendations to coaches. Short-term retention tests after video feedback seem promising in that retention of learned landing technique was achieved.\textsuperscript{40} Better retention implies that less time is needed and consequently more time can be spent on other exercises.

\textit{Video feedback}

Our results showed that the males (who received video feedback) imitated the expert performer and therefore increased the amount of expert and athlete overlap during the landing task. Furthermore, these males showed a changed landing pattern during posttest. Visual feedback seemed to promote motor learning during landing tasks, which is in line with others.\textsuperscript{49-52} The video feedback with overlay method may have encouraged whole body awareness and a realistic feeling.\textsuperscript{53} The effect of video feedback may be attributed to the function of mirror neurons. Mirror neurons are visual motor neurons that fire when a task is executed and when an action is passively observed.\textsuperscript{54} These mirror neurons can connect visual and motor characteristics. The mirror neuron system may have been triggered by watching the landings of the expert and athlete, resulting in imitation of the observed jump landing.\textsuperscript{55} The present findings add to previous studies that showed positive effects of combined video expert and self-feedback.\textsuperscript{49-51}

The overlay method used in the video feedback is new and allows for direct comparison of one’s own landing pattern with an expert. The expert model functions as a target movement pattern. In order to facilitate comparison, a simplified video was shown in the form of a body contour. This new type of video feedback may assist in resolving problems with adherence and implementation. We think that video feedback with overlay method will improve the transfer of learning correct landing patterns from a training session to the field as it stimulates automatic
learning processes. This may facilitate implementation in real sports settings. However, long-term results of the video feedback with overlay method need to be examined before we can provide recommendations to coaches. We suggest that by using video feedback ACL injury prevention programs can be optimized and can be made more applicable to practice. For instance, the trainer could record a video of one of the athletes that shows a correct two-legged jump-landing. This video could then be presented to other team members during practice. After that the athlete’s own performance can be recorded and presented to the athlete. A simple camera or a mobile application for smartphone or iPad, developed for providing video feedback, could be used.

Sex-specificity of injury prevention
In Chapter 2, 3, 4 and 6 sex differences or a lack of sex differences have been described regarding landing technique, dynamic stability, effect of knee injury prevention programs and effect of video feedback. These sex differences are in line with the differences in ankle sprain and ACL injury occurrence that have been reported for male and female athletes.

Most high quality studies in Chapter 4 were published in the last decade, indicating an increase of attention for injury prevention research and an integration of sports science and sports medicine. However, knowledge about which screening tests and injury prevention programs are suitable for females and males is limited. As our systematic review indicated (Chapter 4), literature on the effect of knee injury prevention programs for males is scarce. Another interesting finding was that in Chapter 2 none of the included studies differentiated between screening tests for males and females. Sex differences in landing technique have been reported. It is therefore very likely that risk factors for male and female athletes are not the same. For instance, female athletes tend to land with less knee and hip flexion and more knee valgus during a stop jump task. An analysis of ACL injuries in male athletes showed that a relatively straight knee and knee valgus (but no dynamic valgus) were often reported mechanisms. If risk factors for knee injuries differ for males and females, this would mean that males and females need a different approach or prevention program to modify these risk factors. Consequently, ACL injury screening tools and prevention programs may need to be sex-specific.

The finding that males seemed to benefit from the video feedback (Chapter 6), while the females did not, emphasized the importance of specifying ACL injury prevention programs. One other study found comparable results. In this study, males who received self-video feedback showed the largest changes in their landing
technique. Females did not change their landing technique after the video feedback. The authors suggested that females might need additional (verbal) feedback in order to be able to change their movement patterns. Indeed, a previous study showed that female adolescent volleyball athletes improved landing technique after a combination of video and verbal feedback. It seems that video feedback alone is not sufficient to change landing technique in females. They may need additional information. Keeping in mind the reported benefits of EF instructions, verbal EF instructions could be added to video feedback.

Furthermore, sex differences in dynamic stability were reported in Chapter 3; males reported a worse dynamic stability compared to females. These findings suggest that sex differences need to be taken into account in studies that include dynamic stability tests and in the development of preventive training programs for ankle injuries.

Lessons learned based on results

Injury prevention model
The development of screening tools based on risk factors for lower extremity injuries is needed to inform injury prevention programs. However, the development and validation of screening tools does not align with (one of) the steps of the injury prevention models by Van Mechelen et al. and Finch. Screening for injury risk involves more than studying etiology and mechanisms and it is forms relevant input for the development of prevention programs. We suggest that the TRIPP framework be extended by inserting a step for the development and validation of screening tools (step 2a, Figure 7.1). Recently, Bahr introduced steps needed for the validation of screening tools. We suggest that these steps could combined with the TRIPP framework. The new step for screening tools should include (1) determining a strong relationship between a certain marker and injury risk and (2) examining whether the screening test can predict injuries in several relevant populations. Furthermore, in steps 4 and 6 of the TRIPP framework, attention should be directed towards differences in efficacy of interventions based on screening compared to interventions not based on screening (universal programs).

It should be noted that the predictive value of the injury screening tests is not yet sufficiently validated. In our opinion this does not mean that these screening tests are not relevant to use in the field. They may still provide important characteristics of the athletes that may be linked to injuries. Based on the data gained by screenings, prevention programs can be adapted to the individual athlete.
Furthermore, sex differences should be taken into account. Sex differences seem to be present in all steps of the TRIPP framework. Therefore, the injury prevention steps should be run separately for male and females. Examples are separate risk factor analyses and screening tool development for males and females and developing ACL injury prevention programs specific to each sex.

**Figure 7.1.** Theoretical framework for injury prevention. The inner circle (grey) is the injury prevention sequence. The outer circle (blue) is the TRIPP framework. Step 2a (orange) is added. Adapted from Van Mechelen et al. and Finch.

**Applicable, sport-specific & predictive screening tools**

Based on the results of our review we suggest that research should focus on developing ACL injury, strength and balance screening tools that are predictive as well as applicable in the field on large-scale. The sport-specificity of the tasks used in screening tools needs to be improved as well. For the measurement of the DSI and landing technique in Chapter 3, 5 and 6, the Vicon motion analysis system was used. In terms of practical applicability, most medical or training staff members do not have access to this system. The development of simple, easy-to-use predictive screening tools is of great importance. Additionally, the context is not only an important element in implementation of prevention programs, this is important for imple-
menting screening tools as well. Screening tools need to be adopted by coaches and their athletes. Therefore, they need to know how to execute and interpret these tests.

It is important to note that the type of instruction could matter when examining sport-specificity. EF instructions improve the transfer of one task to another (e.g. two-legged jump-landing task to side-step cutting maneuver), still sport-specificity may need to be considered. When using EF instructions, the transfer of learning a task under stable conditions to situations with less stable conditions is improved. Additionally, when IF instructions are used it should be considered that transfer to other tasks and to the game may be impaired.

We have to keep in mind that often times a combination of factors leads to the occurrence of an injury. This thesis focused on modifiable risk factors (i.e. landing technique). We acknowledge that there are more risk factors that may need to be taken into account. Some studies that were included in Chapter 2 used multi-variate analyses to calculate injury risk. In the search for risk factors and screening tests for lower extremity injuries, a multi-factorial approach should be incorporated.

**ACL injury prevention**

**Implementing injury prevention program in warmup**

Based on the development and evaluation of ACL injury prevention programs some lessons were learned. Our warmup program was implemented in winter, therefore some training sessions had to be canceled due to cold weather, and additional running exercises had to be included prior to the warmup. For this reason, weather conditions need to be taken into account during the implementation of an ACL injury prevention program. For instance, the advice is to implement the program at the start of a season (summer), when the weather is still good. Also, during winter, an alternative program should be available in case training is canceled due to cold weather. For outside training sessions during winter, a suggestion would be to modify trunk stability exercises (no exercises on the floor) and reduce the duration of breaks to prevent the athletes from getting cold. In other words, the program should be flexible. Also, a large amount of people go to the gym to exercise, therefore another option would be to include trunk and stability exercises in their gym training.

**Adherence of coach and athlete**

Our experience was that motivation of coaches to incorporate an injury prevention program in their training schedule needed to be encouraged. This is in line with previous research. Athlete and coach adherence is an often-reported issue for the
implementation of ACL injury prevention programs. In Chapter 4 differences in adherence between both intervention groups were found, which could have influenced the results. In the field, athletes still needed to be motivated to perform the preventive exercises. A short program integrated into a warmup, inclusion of coaches and athletes in the development of ACL injury prevention programs, as well as showing positive results from these programs could enhance adherence to the program.

Prior to the start of the program, individual sessions with the coaches were scheduled to inform them about benefits and content of the warmup (Chapter 5). Moreover, during the intervention several evaluation sessions were scheduled. This resulted in high adherence to the intervention. Only a few sessions were canceled due to weather circumstances. Two trained students provided the warmup prior to each training, which could have increased overall adherence to the intervention. In contrast, another study demonstrated that coaching workshops increased motivation, but did not translate to increased adherence. In this particular study, coaches had to provide the warmup themselves. Ideally, the warmup is provided by the coach or someone from the (medical) staff, as the trained students will only be available during the research project. This means that future research needs to focus on ways to increase coach adherence and motivation. Some studies have already spent attention to this topic showing that implementation context should be taken into account, as well as opinion or experiences of end users (i.e. coaches and athletes).

One of the arguments of coaches who implemented an ACL injury prevention program is a belief that it enhances performance of their athletes. In other words, it would be even more interesting for coaches if the changes in injury risk or landing patterns are accompanied by performance enhancement. A recent study demonstrated that landing technique improved while jump height was maintained after video feedback or EF instructions. Moreover, a review showed that use of an EF of attention resulted in significantly better motor performance and jump-landing technique compared to an IF. Most included studies in this review performed the experiments in a lab setting. However, the ultimate goal is to accomplish the same results in a real-practice setting. Collection of data during training sessions and competition might assist in determining effect of EF on performance and injury risk. In summary, we think that collaboration sessions for coaches should include information on performance enhancement.

Instruction frequency
The instruction frequency was equal for the IF and EF intervention groups (Chapter 5). Therefore, the EF group may have benefited from the frequent instructions,
whereas the IF group may have been overloaded with information. A reduced frequency of IF feedback is advised, in order to prevent reduced motivation. 

During the training sessions we noticed that the repetition of instructions was too high. It was not clear to athletes why instructions were repeated after each exercise and may have annoyed them. Giving the athlete control over the frequency of instructions may improve the effectiveness of motor learning and motivation of athletes. 

Therefore, in our last research project (Chapter 6) we tried to enhance motivation of athletes by using a (semi) self-controlled feedback.

**Use of self-expert**

In Chapter 6, each athlete was matched with an expert based on sex and body height. We acknowledge that each athlete has his or her own optimal movement pattern due to each athlete having their own unique characteristics (i.e. body size estimates, limb length, learning style or preferences). The use of a self-expert in the video feedback with overlay method could make it easier for the athlete to identify with.

**Transfer and retention of tasks**

“Motor learning is defined as the process of an individual’s ability to acquire motor skills with a relatively permanent change as a function of practice or experience”.

Consequently, a limitation of this thesis was that no long-term retention or transfer tests were performed. Performing these tests would be necessary in order to determine if the changes in the execution of a motor task are permanent. Other research from our group using the same video feedback method showed short-term retention of the learned task. It seems that the video feedback is a promising method. Furthermore, it is suggested that feedback with an EF facilitates transfer of learned motor tasks to a practice setting. However, in this thesis, landing technique was not measured in a practice setting. Therefore, we cannot confirm if athletes showed altered movement patterns during actual practice or competition.

**CONCLUSIONS AND FUTURE RESEARCH**

At the start of this thesis, the injury prevention model by Van Mechelen et al. and Finch were explained. The first part of this thesis focused on screening tools for lower extremity injuries in team sports. We suggested that the development of screening tools does not align with one of the steps of the TRIPP framework and therefore may need to be extended by a step to include the development and validation of screening
tools (step 2a, extended TRIPP). We found that there are several screening tools available to screen for lower extremity injury risk (Chapter 2), including anthropometric, flexibility, strength, balance and ACL injury screening tests. Some of these predictive measures (ACL injury, strength and some balance tests) were limited in their practical applicability and sport-specificity, while there other promising reliable screening tools were easy to use, however predictive ability of these measures for injury risk has not been determined yet.

Further work is required to find predictive sport-specific, inexpensive and easy-to-use screening tools for lower extremity injuries (step 2a, extended TRIPP). In addition, it would be valuable to find out further what characterizes a risky landing technique in males. Screening tools need be developed to measure landing technique. The effect of injury prevention programs on these male injury risk factors is another interesting topic for future studies.

The second part of this thesis included an evaluation of injury prevention programs and their ability to reduce risk for ACL injuries by improving landing movement patterns (step 3 & 4, TRIPP). Several ACL injury prevention programs have been developed and evaluated (Chapter 4). Important to note is that research on ACL injury prevention in male athletes is scarce. Considering the benefits of EF instructions and feedback, we think that using EF or video instructions or feedback or a combination of these two may help to improve current programs. Positive results were found for the video feedback after a short–term retention test, which may imply that less time is needed for prevention programs (Chapter 6). This thesis adds to the growing body of knowledge on benefits of EF feedback in ACL injury prevention. Our studies have provided important practical insights that can be used to optimize ACL injury prevention programs and make them applicable for real-sports situations.

The implementation of ACL injury prevention in training sessions was challenging (Chapter 5). Based on the results of this thesis we suggest that research should focus on implementation of screening tools and developed ACL injury prevention programs in a real-sport situation (step 6, TRIPP). In addition, the developed ACL injury prevention programs with EF instructions and video feedback need to be evaluated on their effect on ACL injury rate.

The potential of using EF instructions in a warmup program needs to be further explored. Although short-term posttests were performed in Chapter 5 and 6, further studies that add long-term retention tests and transfer tests to the test protocol are necessary to determine if changes in landing technique are permanent. In general,
future studies that include one or more steps of injury prevention should take into account sex-specificity.

PRACTICAL APPLICATIONS

Based on the results of this thesis, advice can be given to coaches, trainers and medical staff about screening tools and ACL injury prevention programs.

Screening (step 2a, extended TRIPP)
- Although predictive ability and sport-specificity of current screening tools need to be improved, a general recommendation to coaches and medical staff is to perform preseason screenings.
  In this thesis a list of screening tools for lower extremity is provided that could be used in the field. These screenings not only provide insight in which athletes are potentially at a greater risk to sustain an injury, but they also inform about the current state of the athlete.
- Coaches and medical staff need to recognize sex differences in screening.
- A multi-factorial approach should be incorporated; for instance by including screening tests for balance, strength and landing kinematics and kinetics.

ACL injury prevention programs (step 3 & 4, TRIPP)
- Integrate ACL injury prevention program into regular warmup.
- A program of short duration is advised.
- To reduce knee valgus and enhance knee flexion, a neuromuscular training program with plyometric and strength exercises needs to be included. These exercises should be combined with verbal or video feedback.
- Individualize the training program based on screening; a one-size fits all approach should be avoided.
- Account for sex differences in ACL injury prevention programs.
- Use of EF instructions combined with visual feedback is recommended.
- A self-controlled feedback strategy is advised.
- Use of a self-expert may be beneficial.
In addition, for future implementation of injury prevention programs it is recommended to:

- Increase the motivation of coaches. In collaboration sessions coaches can be included in the process of developing injury prevention programs,\textsuperscript{42} for instance, by asking their feedback and investigating their needs for an injury prevention program. A train-the-trainer session can be integrated as well and might be helpful in improving implementation by increasing their competency and self-efficacy.\textsuperscript{42} In the education of coaches, the relative advantage, compatibility and complexity of tasks should be taken into account.\textsuperscript{2} Additionally, availability of new, portable and gamified video feedback technologies may increase motivation of coaches to implement.\textsuperscript{80}

- Increase the motivation of athletes. Athlete adherence may also be enhanced by variance in exercises, self-choice of exercises (learner autonomy), self-controlled feedback, performance enhancement, proper supervision and reduction of injuries.\textsuperscript{5,64,74,77,81,82} Also, having fun, setting goals and easy comparison with peers may help in increasing adherence.\textsuperscript{74}
REFERENCES


Summary and general discussion


