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The Extent of Neuromuscular Training in Modifying Biomechanical Risk Factors for ACL Injury in Female Basketball Players

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Abstract. Female basketball players are at a substantially higher risk of experiencing Anterior Cruciate Ligament (ACL) injuries than male players. Many of these are non-contact injuries that happen during deceleration, landing from jumps, and changes in direction. Neuromuscular training (NMT) has drawn growing interest, as it aims to modify the potentially preventable movement patterns that contribute to ACL injuries. This essay examines the extent to which NMT modifies the biomechanical risk factors associated with ACL injuries in female basketball players. Research has shown that NMT can produce meaningful improvements in several biomechanical variables, particularly dynamic knee valgus and lumbopelvic control. However, its effectiveness is not guaranteed, and factors such as duration, specificity, and intervention content must also be considered. Programs that combine plyometrics, strength, balance, and movement feedback appear to be more effective than interventions focused on agility alone. Although some studies suggest NMT reduces injury incidence, most available research measures biomechanical change rather than tracking ACL injuries directly. As a result, the evidence supporting NMT is strongest with respect to the modification of biomechanical risk factors, though the degree to which these alterations translate into long-term ACL injury prevention remains far less established. These findings can offer a useful reference for designing ACL injury-prevention training programmes for female basketball players.

Keywords: ACL injury, neuromuscular training, dynamic knee valgus, landing mechanics, female basketball players

1. Introduction

The knee is subjected to significant forces in basketball due to the constant jumping, landing, deceleration, pivoting, and changing direction. Epidemiological evidence shows that female basketball players have a significantly higher risk of anterior cruciate ligament (ACL) injuries than male athletes, and the vast majority of these injuries are non-contact injuries—that is, they occur without direct physical contact with an opponent. Such non-contact injuries are more important for injury-prevention research as they relate to the athlete's own movement patterns and neuromuscular control.

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This paradigm shift has redefined the perception of ACL injury, moving it from a seemingly unpredictable event to a condition with identifiable, modifiable biomechanical and neuromuscular risk factors. As a result, inadequate landing mechanics, excessive knee valgus, insufficient trunk and hip control, and aberrant muscle activation patterns have emerged as core targets for injury prevention interventions. Neuromuscular training has been designed based on the idea that it is possible to change these movement patterns by repetition, building strength, balance training, and feedback.

However, it is important to note that improvements in biomechanical parameters resulting from neuromuscular training do not directly equate to actual prevention of ACL injuries. The question is whether neuromuscular training can change the biomechanical risk factors for ACL injury in girls playing basketball. The emphasis is particularly directed toward basketball players, as the repeated jumping, landing, deceleration and cutting actions seen in this sport could affect the pertinence of results from other sports.

Answering this question has value on several levels. Identifying effective training strategies for mitigating injury risk factors is relevant for female basketball players, as ACL injuries can result in lengthy rehabilitation, lost playing time, and long-term consequences for knee health. For coaches, athletic trainers and physiotherapists, it can be useful in the selection and design of prevention programs to focus on the appropriate prevention mechanism rather than a general conditioning program that has the potential to influence injury-related movement patterns. In general, defining the scope of NMT and what it is not capable of doing will help to differentiate the biomechanical effects of NMT from claims that are sometimes made about the effects of NMT on injury prevention.

2. Physiological and biomechanical risk factors

The risk factors for ACL injury in female basketball athletes can be divided into two groups: non-modifiable factors, such as anatomical structure and hormonal influences, and modifiable factors, such as neuromuscular and biomechanical factors that may respond to training.

Anatomical and physiological factors have been identified that contribute to the higher risk of ACL injury in female athletes and are less likely to change with training. For instance, the dimensions of the intercondylar notch and the Q-angle have been studied as risk factors for ACL injury. Hormonal changes: fluctuating levels of hormones, such as estrogen throughout the menstrual cycle, have also been linked to changes in the properties of the ligaments and laxity. These can lead to a general susceptibility that is not fully eradicated by training.

Several biomechanical and neuromuscular factors, however, are potentially modifiable. Female athletes have been reported to exhibit higher dynamic knee valgus when landing and during other athletic movements. Dynamic knee valgus is defined as a movement of the knee towards the midline of the body and is linked to higher knee abduction loading. Hewett et al. [1] have shown that biomechanical assessments of knee valgus loading and neuromuscular control were able to predict the risk of ACL injury in female athletes prior to injury.

Landing strategy is also important. Other female athletes exhibit relatively stiff landing patterns with less knee and hip flexion and more impact absorption in the lower limb. Variations in trunk positioning and hip control can also alter the forces transmitted across the knee joint. Muscle coordination and activation timing are also important since the proper timing of the hamstrings, quadriceps and hip and trunk muscles is associated with dynamic knee stability.

These modifiable movement patterns are of particular relevance in basketball, a sport that demands repeated exposure to high-demand maneuvers including high-speed decelerations, single-leg landings, pivoting, and unanticipated directional changes. The main reason for the focus on

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NMT is that it primarily addresses the biomechanical and neuromuscular factors that may be modified via training, as opposed to the anatomical makeup of an athlete.

3. The impact of neuromuscular training on these factors

3.1. Landing mechanics and frontal-plane control

One of the biomechanical variables that seems to be relatively consistent in response to neuromuscular training is dynamic knee valgus. Rostami et al. [2] examined the effect of an 8-week STOP-X warm-up program consisting of plyometric exercises and movement-technique training in female basketball players with dynamic knee valgus. The intervention resulted in a decrease in the peak knee valgus of participants who had the movement pattern at baseline, and an increase in lumbopelvic control.

This study is consistent with an earlier study of the STOP-X program. Rostami et al. [3] reported significant reductions in knee valgus angle, alongside measurable improvements in both static and dynamic balance, following the targeted intervention. Similarly, Sasaki et al. [4] demonstrated that a training program integrating core and hip strengthening exercises produced reduced knee valgus loading during drop-jump tasks among collegiate female basketball players.

These studies, combined, indicate that NMT may result in meaningful changes in frontal-plane movement during landing. However, the ways in which the programs achieved this differed. The STOP-X program combined plyometrics with movement-technique training [2, 3], while Sasaki et al. focused on core and hip exercises [4], which suggests that more than one training approach can reduce knee valgus. Even so, the effectiveness of NMT seems to be related to the content of the intervention. Training that directly targets landing technique and proximal control seems to be more effective than general agility training. For instance, Wilderman et al. did not observe a significant change in any of several knee kinematic variables associated with the risk of ACL injury with the use of agility training alone [5]. The evidence therefore suggests that exercises need to be targeted to the movement patterns that have been linked to injury, and not just to increasing an athlete's speed or ability to change direction.

3.2. Muscle coordination and strength

Adaptations to the neuromuscular control of the trunk, hip and lower limb are likely to be required alongside the changes in landing mechanics. Sasaki et al. [4] looked at how core-muscle training affects neuromuscular control in female collegiate basketball players. Sasaki et al. investigated how an 8-week core-muscle training program affected neuromuscular control among female collegiate basketball players. Following the intervention, the intervention group demonstrated an increased maximal trunk-flexion angle during landing and a reduced peak knee-valgus moment, whereas no such changes were observed in the control group. This finding reinforces the significance of proximal control of lower-limb movement. Better control of the trunk and hips can help an athlete maintain a more stable body position when landing and minimize the loading on the knee. It is important to note that this study offers evidence of the contribution of core training specifically, and not just the contribution of a multi-component program [5].

However, alterations in neuromuscular control might not happen right away. Movement patterns rely on the coordination and timing of several muscle groups, and repeated exposure to the right movement strategies is probably required for adaptation. In addition, there is limited evidence from the available studies to indicate how long these adaptations last following the cessation of training.

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This restricts the ability to extrapolate from short-term changes in movement behaviour to permanent changes.

3.3. Proprioception and dynamic balance

Proprioception and dynamic balance are another aspect of NMT. Improvements in balance may not seem as directly related to ACL injury risk as improvements in knee valgus, but they may play a role in helping an athlete maintain appropriate lower-limb alignment during unpredictable movements.

A six-week neuromuscular training program was studied in college women's basketball players by Pfile et al. [6], which resulted in improvements in dynamic balance and landing mechanics. Importantly, these improvements were still detectable nine months following the training, suggesting that at least some of the neuromuscular adaptations can be maintained beyond the training period.

There is also some evidence at the injury-outcome level. In a cluster randomized trial using elite and semi-professional female basketball players, Bonato et al. [7] determined that a bodyweight neuromuscular warm-up intervention was associated with fewer serious lower-limb injuries than a standard warm-up. This does not prove that the decrease in injuries was due to improvements in balance, but it indicates that neuromuscular exercises in basketball warm-ups are effective.

The importance of balance may become particularly apparent during game situations. Basketball involves unpredictable landings, fast changes of direction, and fatigue- or opponent-induced movements. The ability to sustain neuromuscular control in these less predictable situations could therefore be the difference between improvements seen in controlled testing and what is achieved during competition.

4. Evidence strength and limitations

Overall, the evidence indicates that NMT does have a considerable impact on a number of biomechanical parameters that are associated with ACL injury risk; however the impact varies in size and consistency across the different parameters. Knee valgus seems to be one of the most responsive factors, as several studies have shown that interventions involving landing technique, plyometrics, and proximal strengthening result in a decrease. Targeted training also seems to enhance trunk and hip control, though there is less evidence of the long-term sustainability of these changes. The direct link between balance improvements and ACL injury reduction is less clear, but improvements in dynamic balance may last longer [8].

The content of the intervention also seems to matter. Generally, multi-component programs integrating plyometrics, strength training, balance drills, and real-time movement feedback demonstrate superior efficacy in modifying biomechanical patterns compared with single-component interventions. Agility training alone, by contrast, may enhance sport-specific movement performance without significantly altering the knee kinematics that increase ACL injury risk. This means that an intervention has to be targeted towards the mechanisms it wants to change.

Another important consideration is the athlete's initial level of biomechanical risk. Athletes with poor baseline movement patterns may see more improvement after NMT than athletes with relatively good movement patterns. However, the magnitude of such benefits is unlikely to be consistent across the entire cohort of female basketball athletes. Most important of all, improvement in biomechanics does not necessarily equal injury prevention. A decrease in knee valgus, for instance, would indicate a change in an athlete's movement pattern, but not that the athlete's risk of an ACL injury has decreased by the same amount. Many biomechanical studies have small numbers

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of participants and measure outcomes over short time periods, while ACL injury is a relatively rare event that can only be studied in larger populations and longer follow-up periods.

Certain research indicates a correlation with injury occurrence. A coach-directed neuromuscular warm-up showed a reduction in non-contact lower limb injuries among female high school soccer and basketball athletes. In a comparable finding, Bonato et al. [7] reported that a neuromuscular warm-up reduced the number of serious lower-limb injuries in female basketball players. These studies add to the evidence that biomechanical adaptations can play a role in meaningful injury reduction. However, they do not prove that any single biomechanical change alone accounts for the observed decrease.

There is therefore strong evidence that NMT alters biomechanical risk factors, and weaker evidence for determining the exact magnitude of the reduction in ACL injury incidence associated with each biomechanical alteration. The multi-component NMT programs for girls in basketball, therefore, should include exercise programs that include plyometric, strength, and balance exercises with feedback on landing technique, which should be continued for a minimum of 6 to 8 weeks and incorporated into regular warm-up drills so that girls continue to train throughout the season.

5. Conclusion

Neuromuscular training seems to influence multiple biomechanical and neuromuscular factors that affect the risk of ACL injury in female basketball players. The most compelling evidence is for a decrease in dynamic knee valgus and an increase in landing and proximal control, especially when programs include plyometrics, strengthening, balance, and a focus on movement technique. NMT is not, however, equally effective. Interventions that focus on the injury-related movement patterns seem more effective than general agility training, and athletes with less effective baseline movement patterns seem to benefit more than those who already move well. In addition, while a few studies have found a decrease in the incidence of lower-limb injuries, many have concentrated on biomechanical changes rather than the incidence of ACL injuries themselves. Thus, while NMT is likely to have a substantial effect on altering biomechanical risk factors, it is less clear whether these changes will reliably lead to long-term ACL injury prevention. The evidence supports the use of NMT as a practical injury-prevention strategy, but larger sample sizes, longer follow-up periods, and direct measurement of ACL injury incidence are required to determine the durability of these biomechanical adaptations and the strength of the association between them and reductions in injuries. Future studies should evaluate the effectiveness of the biomechanical changes in reducing the incidence of ACL injuries in female basketball players over an entire competitive season and look at the amount of maintenance training necessary to sustain these changes following the completion of the training program. NMT should not be considered a single solution, but rather a major piece of a multi-faceted, long-term strategy for preventing ACL injuries.

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