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Anterior Cruciate Ligament Injury Prevention Exercises: Could a Neuromuscular Warm-Up Improve Muscle Pre-Activation before a Soccer Game? A Proof-of-Principle Study on Professional Football Players

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Abstract: Neuromuscular warm-up has been shown to decrease the risk of anterior cruciate ligament (ACL) injury improving muscular firing patterns. All preventive training programs described in the literature have a duration of several weeks. To date, no studies have explored the immediate effect of a neuromuscular warm-up exercise on pre-activation time of the knee stabilizer muscles. Thus, this proof-of-principle study aimed at evaluating the acute effects of a neuromuscular warm-up exercises on the electromyographic activation of knee stabilizer muscles' activation pattern. We included 11 professional football players, mean aged 23.2 ± 4.5 years, from a Southern Italy football team. All of them underwent a standard warm-up exercise protocol at the first day of the evaluation. At 1 week, they underwent a structured neuromuscular warm-up exercise protocol. We assessed as outcome measure the pre-activation time (ms) of rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), and medial hamstrings (MH) upon landing. Outcomes were assessed before and after the standard warm-up and neuromuscular warm-up. Pre-activation time of RF, VM, BF and MH significantly improved only after neuromuscular warm-up ($p < 0.05$); moreover, there was a significant ($p < 0.05$) between-group difference in pre-activation time of all muscles after the neuromuscular warm-up compared with the standard warm-up. These findings suggested that physical exercise consisting of a structured injury prevention neuromuscular warm-up might have an immediate effect in improving the activation time of the knee stabilizer muscles, thus potentially reducing the risk of ACL injury.

Keywords: neuromuscular warm-up; physical exercise; rehabilitation; anterior cruciate ligament injury; soccer players; football

1. Introduction

Anterior cruciate ligament (ACL) injuries affect recreational, competitive, and professional athletes and, in particular, football players with a negative impact on their quality of life [1]. Indeed, a tear of the ACL is considered a noteworthy injury that commonly requires a prolonged period away from competition and need of an adequate rehabilitation plan [2,3]. Although 70% of players return to play (RTP) [2], only two-thirds of players with a complete ACL lesion play at the high level 3 years later [4]. Moreover, ACL injury is related to a higher risk of a knee re-injury [5], and long-term medical disability due to early osteoarthritis occurring in half of the individuals 10–15 years later [6,7].

There are four main situational patterns of ACL injuries in football players: pressing/tackling, tackled, regaining balance after kicking, and landing from a jump. In most cases (81%) a mechanical perturbation causes a high knee valgus loading [8]. When a perturbation alters the equilibrium of a system, a preparatory contraction of the muscles stiffens the joint as a protective reaction to prevent injury with a feedforward mechanism. In particular, the anticipatory contraction of quadriceps and hamstrings muscles protect the joint generating dynamic stiffness and higher stability [9] that could reduce the dynamic knee valgus [10].

Albeit quadriceps strength, lateral-lateral symmetry, and hamstring-quadriceps ratio are important parameters in knee injury [11], neuromuscular control plays a key role in determining the timing of muscle activation [12]. Medina et al. compared muscular pre-activation of selected lower extremity muscles in response to a drop landing, to detect neuromuscular recruitment in young athletes, highlighting the need to improve hamstrings training methods for better neuromuscular control to lower the risk of injury [9].

In the literature, there is strong evidence on prevention exercise programs demonstrating evident benefits in reducing the risk of ACL injury [1]. Most of all, methods based on the enhancement of neuromuscular and proprioceptive control have been shown to decrease the risk of ACL injury up to 51% [13–16], improving muscle firing patterns, and increasing dynamic stability of the lower limb [17]. The improvement in muscle firing is the consequence of an improvement of reactive muscle activity due to a more rapid recognition of unexpected perturbations by the muscle spindle [18,19]. During a sport specific task, co-contraction represents a motor control strategy to dynamically stabilize and protect a joint. Co-contraction improves knee stability when the joint is subjected to high load or shear forces [20]. Specifically, one of the most effective patterns to dynamically stabilize the knee during varus and valgus moment is Quadriceps: Hamstring (Q:H) co-contraction. Unbalanced Q:H co-contraction can contribute to higher knee abduction loads increasing strain on the ACL [21,22]. To date, the preventive exercises programs proposed in the literature [14,15,17,23] have a duration of several weeks to whole season; however, García-Luna et al. [24] have recently reported that an ACL exercise program included in a football warm-up could reduce dynamic knee valgus in the short-term, preventing knee injuries in male soccer players [17]. In this scenario, neuromuscular evaluation by surface electromyography (sEMG) showed to play a crucial role providing a deep view of the behavior of the neuromuscular system [25]. Specifically, it is possible to determine the timing of muscle excitation showing when a muscle turns "on" [25] and to record muscle activation of the knee stabilizer muscles to determine the recruitment order and the time of pre-activation as the start time of contraction before landing. Therefore, this proof-of-principle study aims to evaluate the short-term effects of a neuromuscular warm-up on the knee stabilizer muscles' activation pattern in a team of professional football players.

2. Materials and Methods

2.1. Participants

We recruited the study participants among 25 professional soccer players from a Southern Italy football team playing in the Italian Second League in December 2019. The study has been performed during the season. Inclusion criteria were: (a) age >18 years; (b) playing competitive soccer at National level as their full-time occupation; (c) at least 5-years of experience in the young leagues. We excluded subjects with: (a) lower extremity reconstructive surgery in the prior two years; (b) lower-extremity injuries or unresolved musculoskeletal disorders that prohibited subjects from sports participation; (c) history of involvement in any ACL injury exercise prevention program. Eleven subjects who met the inclusion and exclusion criteria read and signed informed consent.

The examiners were instructed to protect the privacy of the subjects. The study was compliant with the Declaration of Helsinki and approved by the local Institutional Review Board.

2.2. Intervention

All study participants underwent a standard warm-up exercise protocol on the first day of the evaluation. At 1 week, they underwent a structured neuromuscular warm-up exercise protocol. In both cases, before beginning the warm-up, we asked the football players to walk on a treadmill with 10° inclination, 6 km/h speed for 2 min. Participants maintained their normal intake of food and fluids, drinking no caffeine-containing beverages and not eating any food in the 2 h before starting the intervention.

The different warm-up protocols consisted of different exercises:

- Classic warm-up: joint mobility exercises for ankle, knee, hip, cervical and lumbar spine, and glenohumeral joint, agility drills, dynamic stretching for major body segments with full range of motion, and strenght.
- Active warm-up represents the most frequent warm-up scheme preparation before a soccer match especially for team sports [26]. Effects of this type of warm-up are to raise muscle temperature, improve nerve conduction, and increase metabolic rate [27].
- Neuromuscular warm-up: dynamic balance, jumps, side cuts, and change of direction tasks including visual/cognitive distractions (Figure 1).

Figure 1. Squat with ball on two legs stance on balance board.

The exercise scheme included different groups of exercises with the integration of the elastic band during squat, side-steps, Bulgarian-split squat [15,17,24,28]. The main objective of this exercise program is to get a higher consciousness and control of knees and ankles during all the sportive activities. The program included exercises with the ball, balance, and strength, utilizing the balance board. A trainer with a 10 years of experience supervised the correct excution of the exercises and asked athletes to focus on the quality of their movements, most of all improving core stability and keep the "knee over toe" position. Furthermore, the trainer asked athletes to observe their teammates and giving continuous feedback. The duration of each exercise set is 5 min and the cumulative duration 15–20 min. Table 1 describes in detail the exercises for the two different warm-up protocols.

2.3. Electromyography

To perform sEMG analysis, the bold skin was abraded and cleaned to avoid impedance artifacts. The sEMG electrodes were applied to 4 muscles of the dominant leg of each subject (rectus femoris (RF), vastus medialis (VM), biceps femori (BF) and medial hamstrings (MH)) [29]. The electrodes were placed following the recommendations of the European Surface EMG project [29] for the non-invasive evaluation of the muscles (see Figure 2). The RF electrodes were placed at 50% on the line from the superior anterior iliac spine to the superior part of the patella, VM at 80% on the line between the superior anterior iliac spine and the joint space in front of the anterior border of the medial ligament. The MH electrodes were placed over the muscle belly half-way between the ischial tuberosity and the tibial insertion point, at least 5 cm proximal to the musculotendinous junction.

The BF electrodes were placed over the biceps femoris muscle halfway between the ischial tuberosity and the fibular insertion site [29].

Table 1. Exercise for the two different warm-up protocols.

Type of Exercise	Classic Warm-Up	Neuromuscular Warm-Up
Mobility exercises (5 min)		
Joint mobility	✓	✓
Dynamic stretching	✓	✓
Agility drills(30 s per exercise)		
Light run	✓	✓
Knee lift and heel kicks run	✓	✓
Backward running with sidesteps	✓	✓
Parade sideway running with raised arms	✓	✓
Carioca sideway crossover foot running	✓	✓
Intermittent stops forward running	✓	✓
Trunk rotations forward running	✓	✓
Cutting movements	✓	✓
Sprint run	✓	✓
Balance exercises (4 min) on balance board		
Squats (with the ball on one or two legs)		✓
Pushing each other off balance (pair exercise)		✓
Single-limb dead lift		✓
Side-steps with resistance band		✓
Strength and power exercises (5 min)		
Squats (to 80° of flexion)	✓	✓
Bulgarian split squat		✓
Bounding strides		✓
"Nordic hamstring lowers"		✓
Forward jumping		✓

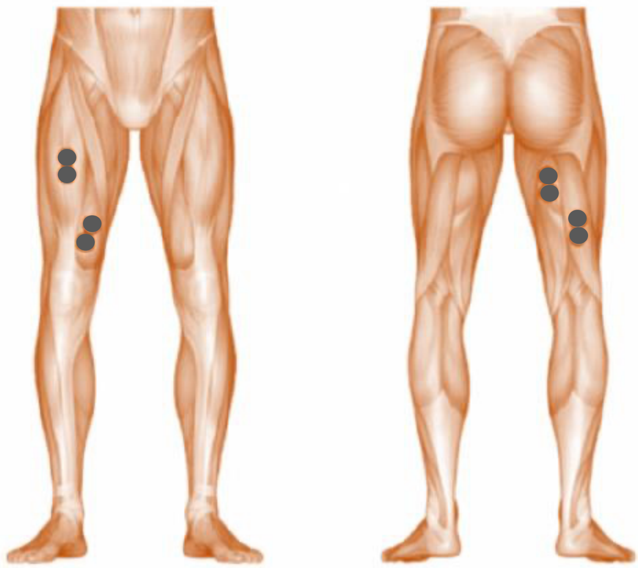

Figure 2. Graphic demonstration of sEMG electrodes placement.

The pre-activation time of knee stabilizer muscles is calculated as the interval lasting between the onset of muscle activation and the ground contact, assessed by surface electromyography (sEMG) (FREE EMG 1000; BTS Bioengineering Spa, Garbagnate M.se—Milano, ITA). The sampling frequency was 1000 Hz. Furthermore, signals were band-pass filtered with a high- and low-pass Hamming filter with cutoff frequencies of, respectively, 10 and 500 Hz, and an additional 50 Hz 80dB/decade notch filter. We rectified the signals and calculated the linear envelope.

Kinematic data were captured using an inertial measurement unit (IMU, G-sensor; BTS Bioengineering Spa, Garbagnate M.se—Milano, ITA). Wireless IMU was positioned to the trunk with an elastic belt. It was used to define the ground contact time and therefore calculate the pre-activation time, as the interval between the onset of sEMG signal and ground contact.

The sEMG and IMU signals were elaborated utilizing the software called sEMG Analyzer (BTS Bioengineering Spa, Garbagnate M.se—Milano, ITA) utilizing the "drop fall" protocol [9–11].

Using a 32 cm platform, each athlete had to position himself on the platform edge with his foot suspended. Each subject had to get off the platform, simply by moving their weight forward, as vertically as possible without jumping or moving the body. Upon landing, the subject had to stop in position for 5 s on the foot.

2.4. Outcome Measures

A physician with 5-year expertise assessed as outcome measure the value of pre-activation time (ms) of knee stabilizer muscles (RF, VM, BF, MH) of the dominant leg, before (T0) and after the intervention (T1).

2.5. Statistical Analysis

R software (version 3.5.1; R Foundation for Statistical Computing, Vienna, Austria) was utilized to analyze data. Data normality was tested with Shapiro-Wilk. Data were described as means ± standard deviations. Significance was tested with Student's *t*-test, using a paired-sample t-test when appropriate. Cohen's d test was used for effect size.

3. Results

From 25 professional football players of the same team competing in the Second Division of the Italian National Soccer Championship, 11 athletes met the inclusion criteria. Demographic data are shown in Table 2.

Table 2. Demographic and career data.

	T0
Age (years)	23.2 ± 4.5
Height (cm)	176.7 ± 10
Wheight (kg)	77.4 ± 12.5
B.M.I (kg/m^2)	23.78 ± 1.5
Senior Club Appearance	164 ± 123.03
Goals	6.67 ± 4.36

Means ± standard deviations for continuous variables.

All the study participants were right-footed. In the pre-interventional phase, there were no statistical significative between-groups differences (p > 0.05) in pre-activation time of the knee stabilizer muscle. After standard warm-up, there were no statistical significative differences in pre-activation time.

After the neuromuscular warm-up, there was an improvement of RF (from 181.72 ± 97.73 ms at T0 to 335.63 ± 225.95 ms at T1), of VM (175.18 ± 87.25 ms at T0; 322.63 ± 163.35 ms at T1), of BF (128.1 ± 64.2 ms at T0; 201.90 ± 103.79 ms at T1), and MH (130.4 ± 54.1 ms at T0; 204.63 ± 108.57 ms at T1).

In the post interventional phase, the between-group difference showed a statistically significant earlier activation of RF, VM, BF, and SM after neuromuscular warm-up compared with standard warm-up (see Table 3 for further details).

Table 3. Differences in pre-activation time (ms) of knee stabilizer muscles before (T0) and after the intervention (T1) comparing the same study population (n = 11), performing firstly standard warm-up and neuromuscular warm-up one week later.

	Standard Warm-Up			Neuromuscular Warm-Up				
	T0	T1	p-Values T1–T0	T0	T1	p-Values T1–T0	Differences between Neuromuscular and Standard Warm-Up (p-Values T1)	Cohen's d
RF (ms)	177.9 ± 92.9	182.0 ± 71.8	0.609	181.7 ± 97.7	335.6 ± 225.9	0.028 *	0.029 *	0.916
VM (ms)	176.1 ± 72.0	181.1 ± 60.7	0.316	175.2 ± 87.2	322.6 ± 163.3	0.004 *	0.013 *	1.148
BF (ms)	127.2 ± 54.9	128.7 ± 43.4	0.856	128.1 ± 64.2	201.9 ± 103.8	0.027 *	0.036 *	0.920
MH (ms)	127.4 ± 55.4	129.3 ± 50.0	0.628	130.4 ± 54.1	204.6 ± 108.6	<0.001 *	0.032 *	0.890

Means ± standard deviations for continuous variables. Statistical analysis performed to assess the intra-group differences was the paired sample t-test; statistical analysis performed to the assess inter-group difference was the t-test. * = $p < 0.05$. Abbreviations: RF: rectus femoris; VF: vastus medialis; BF: biceps femoris; MH: medial hamstrings.

4. Discussion

This proof-of-principle study explored the effect of a neuromuscular warm-up on the activation pattern of the knee stabilizer muscle in professional football players. This study firstly investigated the role of a structured neuromuscular exercises program in improving RF, VM, BF, and MH timing of excitation compared with a standard warm-up, demonstrating a change in muscle activation patterns that could diminish ACL load.

Taken together, our findings showed a significantly increased time of muscular co-contraction of the analyzed muscles at ground contact during landing in subjects undergone a neuromuscular warm-up. Indeed, this aspect could represent one of the most effective knee stabilizing patterns protecting from varus-valgus moments during cutting maneuvers [22]. Moreover, an improvement in the time of pre-activation of VM leads to a better mediolateral quadriceps recruitment pattern, decreasing the apparent valgus dynamic position of the knee and ACL load [10,11]. Increased MH activation time before the foot contact could decrease the time required to stabilize the lower limb before the anterior shear force occurs [30]. Moreover, before the loading phase that occurs during ground contact, it might also dynamically protect the integrity of the knee joint and surrounding structures [30].

Regarding the activation pattern modifications of the knee stabilizer muscle, the statistical analysis showed a significant difference in the pre-activation time of VM, RF, BF, and MH after the neuromuscular warm-up ($p < 0.05$) compared with the standard warm-up, highlighting the importance of neuromuscular exercises in the pre-competition.

Therefore, the combination of changes in neuromuscular activation after neuromuscular warm-up could improve the activation pattern of the knee stabilizer muscle with the potential result to lower ACL load.

To date, the literature has only described the kinematic effect after a neuromuscular warm-up, decreasing the knee valgus angle in both dominant 62.57% and non-dominant 53.34% legs [24]. However, the present proof-of-principle study might give a new insight demonstrating that the timing of the knee stabilizer muscle is the link between neuromuscular training and the reduction of the dynamic knee valgus [10].

Hurd et al. [18] proved that a ten-week neuromuscular exercise program resulted in positive neuromuscular adaptations increasing the neuromuscular coactivation of quadriceps and hamstrings limiting tibial translation in the longitudinal and axial plane. Moreover, Johanson et al. [31] stated that perturbations could excite the afferent pathways providing signals to the muscle spindle. The augmented sensitivity of the spindles induces a higher state of muscle readiness to perturbations, which improves joint stability [18,31]. This aspect corroborates our results and the immediate effects of a neuromuscular warm-up on the overall activation of the thigh muscles. In detail, the reinforcement maneuvers produce gamma effects mainly on dynamic fusimotor neurons [32]. This gamma excitation occurs in muscles during reinforcement maneuvers and causes an "arousal" reaction. The level of fusimotor excitation before an unexpected stretch influences the reaction of the muscle spindle Ia afferents to the stretch. [32]. Polysynaptic input from several afferents identified to cause alpha motoneuron responses arrive to fusimotor neurons. Moreover, the activated spindle afferents have a strong, short-latency influence on the alpha motoneurons [33]. The perturbation should be large and temporally extended to reprogram the transducer for appropriate operation under the conditions anticipated during this extended response [33].

Such an optimized state improves the resolution of the proprioceptive information received by the central nervous system and the afferent signal from unexpected perturbations is driven directly to the final target, in these case the knee stabilizer muscles [33].

Based on these premises, the neuromuscular warm-up represents an appropriately large and temporally extended polysynaptic input and acts as a reinforcement maneuver, exciting the dynamic fusimotor neurons and acutely improving the activation pattern of knee stabilizer muscles.

This athlete-oriented training protocol focuses on balance exercises directing on knee control to not only prevent injuries but also improve dynamic balance; a better landing strategy, preferring two-legged landing, and with flexed knee and hip joint reduces the landing load; strength exercise, the "Nordic hamstring lower" exercise, and single-limb dead-lift exercise, that can act as ACL agonist [17,28]. The program also included perturbation training techniques utilizing a balance board that is seen to improve motor control during game actions that are frequently linked to an ACL injury [18]. The exercise program presented in this study is multidimensional considering several aspects that could lower the probability of knee injury (agility, balance, strength, awareness of at-risk positions of the lower limb).

This proof-of-principle study had some limitations: firstly, the small sample size that could not allow adequate external generalizability; secondly, the possibility that sEMG measurement could be influenced by muscle crosstalk, albeit we tried to minimize it by considering and carefully selecting the appropriate electrode size, inter-electrode distance, and the locations of electrode placement; finally, it was not possible to define which section of the neuromuscular warm-up proposed had obtained the greatest influence in preventing ACL injuries.

5. Conclusions

Taken together, the findings of this proof-of-principle study demonstrated that a neuromuscular warm-up exercise program might improve the pre-activation timing of the knee stabilizer muscles. This immediate effect seems to be due to an improvement of the muscle reactivity via the muscle spindle that quickly identifies unexpected perturbations, thus leading to a potential reduction of the risk of ACL injury. Further prospective studies on wider cohorts are warranted to better clarify the causal relationship between neuromuscular warm-up and a lower incidence of knee injuries.

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