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Armin H. Paravlic[a,b,c], Peter Bakalár[d], Katarina Puš[a,e], Saša Pišot[b], Miloš Kalc[b], Kaja Teraž[b,f], Luka Šlosar[b,e,g], Manca Peskar[b,h], Uroš Marušič[b,e] and Boštjan Šimunič[b]

[a]Institute of Kinesiology, Faculty of Sport, University of Ljubljana, Ljubljana, Slovenia; [b]Institute for Kinesiology Research, Science and Research Center Koper, Koper, Slovenia; [c]Faculty of Sports Studies, Masaryk University, Brno, Czech Republic; [d]Faculty of Sports, University of Prešov, Prešov, Slovakia; [e]Department of Health Sciences, Alma Mater Europaea – ECM, Maribor, Slovenia; [f]Clinical University Department of Medical, Surgical, and Health Sicences,, University of Trieste, Trieste, Italy; [g]Department of Health Sciences and Technology, Institute of Human Movement Sciences and Sport, Zurich, ETH Zurich, Switzerland; [h]Biological Psychology and Neuroergonomics, Technische Universitat Berlin, Berlin, Germany

ABSTRACT

This study evaluated the effects of a neuromuscular training (NMT) warm-up program on injury incidence, neuromuscular function, and program adherence, maintenance and acceptance in adolescent basketball players. A total of 275 players from 20 Slovenian teams (15 ± 1.7 years of age), were randomized into an intervention group (IG, n=129) and a control group (CG, n=146). Over three months, the IG incorporated NMT into their warm-ups, while the CG followed their usual practice. Measurements of body anthropometry, muscle contractile properties, and balance were taken before and after the intervention. Also, the injury incidence, training adherence and maintenance were reported. Both groups showed improved balance, with no significant difference between them. However, IG demonstrated reduced delay times in specific muscles, indicating improved neuromuscular function. Injury prevalence proportion (%) during the whole study period was higher in the control group compared to intervention (IG: 10.9% vs. CG: 23.3%), and incidence rate. Moreover, the incidence rate ratio for sustaining an injury was 2.6 on average (ranging from 0.88 to 7.07 for tendon and muscle injuries, respectively), indicating significantly lower injury risk in IG than CG. These findings highlight the effectiveness of NMT warm-ups in reducing injury risk and enhancing neuromuscular function, emphasizing the value of structured injury prevention strategies in youth sports..

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KEYWORDS
Muscle contractile properties; balance; injury incidence; injury prevalence; training adherence

1. Introduction

Participation in youth sports such as basketball offers many potential benefits for children and adolescents (DiFiori et al., 2018). Despite all the benefits, basketball, with its repetitive jumps during games and training, abrupt changes in direction, running and deceleration, may result in an injury, most often of the ankle and foot; knee, head and neck; and hands, fingers, and wrists (Andreoli et al., 2018). The basketball-related injuries may not only disrupt acute performance but can have long-term consequences, affecting future athletic endeavours and the overall well-being of basketball players (Vaudreuil et al., 2021).

To counter this negative consequences, various basketball-related injury prevention programs were investigated with some of them focusing on neuromuscular training (NMT) (Taylor et al., 2015). However, studies conducted solely on basketball players have yielded conflicting results regarding the effectiveness of NMT programs, which may be attributed to significant methodological heterogeneity in terms of players' sex, age, and the designs of the NMT programs (Cumps et al., 2007; Eils et al., 2010; Longo et al., 2012; Riva et al., 2016; Stojanović et al., 2023). For instance, Cumps et al. (Cumps et al., 2007) investigated the effectiveness of the basketball-specific balance training program on the incidence of ankle sprains in youth basketball male and female players, with an average age of 18 years. They found that the relative risk (RR) of lateral ankle sprains was lower in the experimental group compared to the control condition, with no difference between female (RR = 0.30) and male (RR = 0.29) athletes, respectively. Similarly, Eils et al. conducted a study applying multistation proprioceptive training in 232 players, with an average age of 23 years, from various basketball leagues in Germany. They reported a 35% reduction in ankle sprains in the training group compared to controls (Eils et al., 2010). Considering the effectiveness of NMT-like preventive measures in reducing other injuries such as anterior-cruciate ligament (ACL) tears, two systematic reviews with meta-analysis (Michaelidis & Koumantakis, 2014; Taylor et al., 2015) found that those were not effective in basketball players. This discrepancy in findings may be attributed to the inclusion of only female players in the original studies analysed by Taylor and colleagues. Additionally, similar preventive programs have been shown to be effective in other sports such as football and handball, underscoring the importance of considering the sport-specific demands of

CONTACT Armin H. Paravlic armin.paravlic@hotmail.com;armin.paravlic@fsp.uni-lj.si; Institute of Kinesiology, Faculty of Sport, University of Ljubljana, Ljubljana 1000, Slovenia

basketball, which may influence the success of injury prevention measures (Michaelidis & Koumantakis, 2014). The most recent prospective study not only focused on the NMT warm-up program's previous findings regarding the effectiveness of NMT-like programs in reducing ankle sprain injuries among basketball players but also showed a tendency towards lowering the incidence of knee injuries compared to the control group (Stojanović et al., 2023). This suggests that NMT in a form of warm-up program can be effective in the prevention of a broader range of basketball-related injuries. However, the current knowledge regarding NMT warm-ups in youth basketball (under 18 years of age) is sparse and therefore requires further research (Räisänen et al., 2021). The period of adolescence is particularly important due to periods of peak growth, during which the injury risk may be increased (Zynda et al., 2022).

Despite the scarce evidence of NMT in youth basketball players, there are issues related to the application of these findings in real-world contexts, which do not guarantee their effectiveness (Benjaminse & Verhagen, 2021; Fanchini et al., 2020; Finch & Donaldson, 2010; Lindblom et al., 2014). The low adherence and maintenance of injury prevention programs are among major issues and could be attributed to several factors (Åkerlund et al., 2022, 2023; Benjaminse & Verhagen, 2021; Owoeye et al., 2020; Steffen, Meeuwisse, et al., 2013). These include limited awareness and understanding of the programs' importance; exercise fidelity; and their effectiveness among athletes, coaches and sports organizations (Ageberg et al., 2022; Åkerlund et al., 2023; Barden et al., 2022). Busy training schedules and time constraints may also hinder consistent implementation of the programs (Åkerlund et al., 2023; Barden et al., 2022). Complexity and the need for specialized equipment can make it challenging to integrate injury prevention exercises into regular training routines (Barden et al., 2022). Moreover, some athletes and coaches may underestimate the risk of injuries and therefore not prioritize prevention efforts. The lack of immediate feedback and visible results from injury prevention programs can impact motivation (Åkerlund et al., 2023; Barden et al., 2022) and lead to inadequate supervision and support. While this question is well investigated in other sports such as football (Hanlon et al., 2020) and handball (Naderi et al., 2023), given a different nature of the basketball game, the adolescent basketball population requires further exploration (Andreoli et al., 2018, Hanlon et al., 2020; Taylor et al., 2015). As suggested by Owoeye and colleagues, research on injury prevention programs should focus not only on their effectiveness but also on adherence, as adherence is a key implementation outcome that determines the effectiveness of an intervention (Owoeye et al., 2020).

Therefore, the aim of the present study was to evaluate several aspects of a targeted NMT warm-up intervention program in adolescent male basketball players implemented during their training practice and competition regarding i) neuromuscular function; ii) adherence, maintenance and acceptance of intervention; and iii) injury incidence, respectively. By comprehensively examining these factors, we sought to provide a comprehensive and evidence-based evaluation of the NMT warm-up intervention program's effectiveness and practicality for injury prevention in adolescent basketball players. The insights gained from this research could contribute to the enhancement of the overall understanding of injury prevention strategies and potentially inform the development of targeted and sustainable NMT warm-up programs for adolescent basketball players.

Based on the existing body of literature and the expected benefits of the NMT warm-up program on injury prevention, we hypothesized that adolescent basketball players who underwent the NMT warm-up intervention program would experience a lower incidence of basketball-related injuries compared to adolescent basketball players from the control group. Also, we believed that the high adherence to the NMT warm-up program would be achieved, and the overall NMT warm-up program design and implementation would be positively rated by coaches and players.

2. Methods

2.1. Participants

Initially, 275 male adolescent basketball players (Table 1), from 20 Slovenian competitive teams (under 15-year groups and under 17-year groups; categorized as tier 2, namely, trained/developmental athletes (McKay et al., 2022)), were recruited for the study. Ten teams were randomized in an intervention group (IG), while others remained in a control group (CG). Specifically, a general concept of a study was presented to the Slovenian basketball association and the information was passed to basketball teams with under 15- and under 17-year groups. The first 20 teams were selected, and written consent was obtained from parents of adolescent basketball players.

The inclusion criteria for basketball players were as follows: males, ages 13–17 years, >2 years of basketball training, membership of the competitive basketball club, and signed written consent by parents. We excluded recreational, injured, and acutely sick players.

Table 1. Participants of the study.

	Pooled participants	Intervention group	Control group	p-value (between groups)
N	275	129	146	
Age/years	15.0 (1.7)	15.0 (1.6)	15.1 (1.7)	0.436
Body height/cm	174.9 (11.6)	174.6 (9.9)	175.2 (12.9)	0.652
Body mass/kg	64.7 (15.0)	65.1 (13.1)	64.4 (16.6)	0.701
Body mass index/kg/m^2	21.1 (5.8)	21.2 (3.2)	21.0 (7.4)	0.736

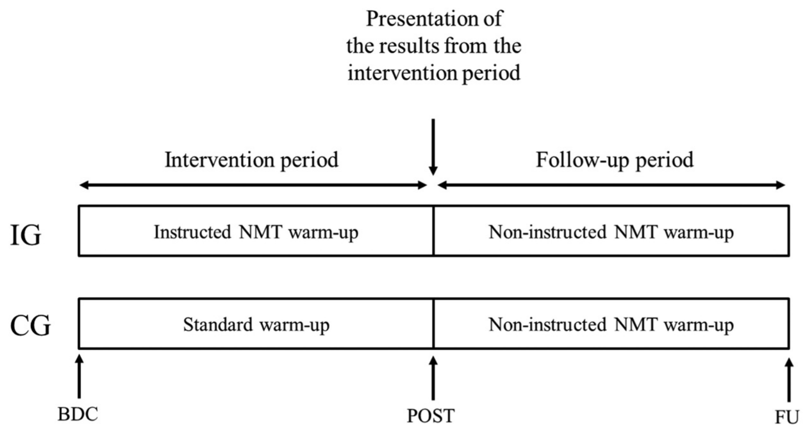

Figure 1. Graphical representation of the study design. Intervention (IG) and control (CG) groups underwent 6-month study design with only IG being subjected to 3-month neuromuscular training (NMT) intervention. Assessments were done at baseline (BDC), post intervention (POST), and post follow-up (FU) periods.

2.2. Study design

The cluster-randomized study design was approved by the Ethical Committee at Science and Research Centre Koper (no. 0624–9/22; 2 February 2022). Figure 1 presents the study design. After randomization, a baseline assessment (BDC, March 2022) was done with detailed explanation of all study procedures to team stuff. Afterwards, the IG followed a 3-month NMT (see description below) instead of normal warm-up. While CG followed their usual warm-up procedures. After a 3-month intervention period, we reassessed (POST, June 2022) all teams, analysed the data and prepared a feedback presentation to all teams. After recognizing all the results of the intervention phase, all teams could decide to continue to use (in IG) or start to use (in CG) for the next 3-month period until final, follow-up reassessment (FU, September 2022). The NMT intervention started after playing 14 (out of 18) games in national championships and lasted during the preparatory season. FU were done just before the new championships started.

2.3. Neuromuscular training

NMT was coach-led intervention, implemented as a part of a structured warm-up, which includes running, agility, balance, plyometrics, and strengthening exercises. The intensity of warm-up was moderate, and the focus was on proper movement technique execution. Therefore, we pre-recorded 50 exercises that were available to coaches. Coaches could then freely choose the amount and progressiveness of the exercises for their team. Exercises were designed with a collaboration of the Slovenian basketball federal association team coach for younger selections to cover all important general and specific motor abilities and were made available online through their smart phones (https://www.zrs-kp.si/index.php/paripre-video/).

2.4. Measurements

Collection of data (body characteristics, neuromuscular properties, balance, and cognition) was done at BDC and POST in basketball team premises. First, body anthropometry was examined, being followed by skeletal muscle tensiomyography, body composition, then balance, and at the end an assessment of cognition. All assessments were done within the timeframe of a usual training practice session (between 8 and 11 AM).

Acute injuries were registered after medical attention and the inability of basketball players to participate in regular basketball training for at least 48 hours (or at least two training sessions).

Body height and mass were measured to the nearest 5 mm and 0.1 kg, respectively, using a stadiometer and scale (LIBELA ELSI, model SIGMA 5NP4, Celje, Slovenia). Furthermore, a body mass index was calculated by dividing the body mass in kilograms by the square of body height measured in metres. The lower limb length was assessed from the iliac crest to the lateral malleolus for the purpose of balance performance normalisation.

Tensiomyography (TMG) of vastus lateralis (VL), biceps femoris (BF), and gastrocnemius medialis (GM) muscles was done on both legs. TMG measurements were performed as reported elsewhere (Paravlic et al., 2022; Šimunič et al., 2018) isometrically using electrically evoked maximal twitch contractions. For VL, participants laid supine with the knee angle fixed at 30° flexion (where 0° represents a fully extended knee joint). For BF, participants lied prone with the knee angle fixed at 5° flexion. For GM, participants lied prone with the ankle in a neutral position. Foam pads were used to support the joints. A single 1 ms maximal monophasic electrical impulse was used to elicit maximal oscillation and enlargement of the muscle belly. These oscillations were recorded using a sensitive digital displacement sensor (TMG-BMC Ltd, Ljubljana, Slovenia) that was placed on the surface of the skin over the mid belly of the muscle of interest. The anode and cathode were placed 5 cm distally and proximally from the sensor, respectively. If needed, the measuring point and electrode positions were adjusted to obtain maximal TMG amplitude (Dm) of the muscle belly response. Initially, the stimulation amplitude was set just above the contraction threshold and then gradually increased until the Dm of the radial twitch displacement increased no further. From two maximal TMG responses, a contraction time (Tc), delay time (Td) and radial velocity (Vr) were calculated, and the average was used for further analysis. Td was defined as a time from electrical impulse to 10% of Dm. Tc was defined as the time for the amplitude to increase from 10% to 90% of Dm.

The Vr was calculated as a ratio between 0.8 Dm and the Tc (Langen et al., 2022). Following these guidelines, a TMG Td, Tc and Dm results are highly intra- and inter-rater reliable (Martín-Rodríguez et al., 2017).

The body composition was measured by multi-frequency bioimpedance analysis (BIA 101, Akern Srl, Firenze, Italy). The assessment was performed immediately after TMG assessment to assure 30-minute supine rests on the right body site with tetrapolar electrode position at the hand and foot instep. The proportion of fat mass (FM in %) and fat-free mass (FFM in %) was recorded. FM% estimation by BIA 101 showed an excellent agreement (ICC = 0.94) and low random error (2.98%) when compared directly with dual-energy X-ray absorptiometry (Rojano-Ortega et al., 2024)

Dynamic balance was evaluated by the Y balance test; after the standardized 5-minute warm-up, the participant stood in the middle on one leg while reaching out in three different directions (in the order: anterior, posteromedial and posterolateral) with the other leg. After the recorded reach distance (to the nearest 0.5 cm), a normalization by the leg length was done. Hands were placed on the hips. The participant repeated each reach three times and the best result was taken for the analysis.

Only uninjured players were included at BDC. Furthermore, the incidence of injuries was recorded at bi-weekly periods during the whole intervention and follow-up periods. During a phone interview with the team staff (coach or medical team member), an electronic form of the FIFA Injury Reporting Protocol was filled out for each injury (Fuller et al., 2006).

Adherence and maintenance of a NMT intervention were performed at the monthly period during the intervention period (only in IG) and during the follow-up period (in IG and CG), asking (i) how many sessions were performed; (ii) how many NMTs were done during these sessions; (iii) in average, how much time was used for one NMT; (iv) in average, how many neuromuscular exercises were used; and (v) which basketball players missed more than five training sessions? All questions were asked for training sessions and competitions.

Acceptance was assessed only once, at FU, by agreeing/disagreeing with these statements: (i) physical activity-related injuries are preventable; (ii) physical activity-related injury prevention is important; (iii) physical activity-related injuries are decreased if NMT is used; and (iv) we will use NMT in the future. Team coaches answered as follows: (1) strongly disagree, (2) disagree, (3) neither, (4) agree, and (5) strongly agree. Furthermore, team coaches answered to additional two open questions: (i) which barriers prevented you to use the NMT intervention and (ii) do you perform any additional systematical physical activity-related injury prevention program?

2.5. Data analysis

Statistical analysis was performed with SPSS statistical software (version 29.0, IBM Inc, Chicago, IL, United States of America). After confirming the normality and homogeneity of the data distribution, a t-test for independent samples was used to check for group differences at BDC. Later, a mixed linear modelling was used for every study outcome. A histogram, QQ plot, and Shapiro–Wilk test was used to confirm the normality of the data. Afterwards, a Leven test was used to confirm the homogeneity of the distribution. In a mixed linear model, participants were classified as random factor, whereas the group (IG and CG) and time (BDC and POST) were classified as fixed factors. If the significant main interaction effect (time * group) was observed, we applied a post-hoc analysis with Bonferroni's correction of p-value to compare time effects in each group separately. All statistical decisions were made at $p \leq 0.05$. As a mixed linear model does not provide standard deviations, we reported 95% confidential intervals (95% CI) as a measure for the variance of the distribution, parameter estimate and standard error. Furthermore, injury incidence was reported in absolute numbers as well as an injury incidence rate for number of injuries sustained per 1000 player-hours. To compare the effectiveness of the intervention on injury occurrence, the incidence rate ratio (IRR) for sustaining injury with 95% CI was calculated as incidence proportion in CG divided by incidence proportion in IG (Ranganathan et al., 2015), and calculated by MedCalc software (https://www.medcalc.org/calc/index.php). The incidence rate (IR) with 95% CI was calculated by the following formulas:

$$IR\ (per 1000\ hrs) = \frac{total\ number\ of\ injuries}{total\ hours\ of\ exposure} \times 1000 \quad (1)$$

$$95\%\text{CI of IR} = \text{IR} - 1.96 \times \text{SE} \quad (2)$$

$$\text{SE of IR} = \sqrt{\frac{total\ number\ of\ injuries}{total\ hours\ of\ exposure}} \quad (3)$$

SE – standard error, IP – incidence rate.

3. Results

In total, 275 participants were initially enrolled in the study (age 15.0 ± 1.7 years) and randomly assigned to IG ($n = 129$) and CG ($n = 146$) (Table 1). The IG conducted an average of 16.3 NMT sessions during the 3-month intervention period, with an adherence rate of 91.1% (Table 2). On average, players in both groups spent 172.2 hours on training and 18.1 hours on matches.

3.1. Neuromuscular function

Compared to CG, IG experienced decrement of Td in VL ($p = 0.024$) or unchanged values in GM ($p = 0.272$) and BF ($p = 0.389$), while in CG, Td values increased at POST (in VL Td: $p = 0.013$; in GM Td: $p < 0.001$; and in BF Td: $p = 0.004$). Additionally, GM Tc remained the same in IG ($p = 0.971$), while it increased in CG ($p < 0.001$) at POST (Table 3). Only in GM, Vr interaction was found ($p = 0.049$), showing an increase in IG ($p < 0.001$) but not in CG.

3.2. Injury prevalence and incidence rates

Injury prevalence proportion (%) during the whole study period was higher in the control group compared to intervention (IG: 10.9%; CG: 23.3%, Pearson Chi-square = 7.350, $p = 0.007$). In general, when IRs considered during the whole study were found to be 0.91, 1.01, and 9.55 per 1000 player-hours for

Table 2. Acceptance, maintenance, and adherence to the intervention program.

	Intervention group		Control group	
	Intervention period	Follow-up period	Intervention period	Follow-up period
Training				
Adherence/%	91.1	60.2	0	40.7
No of exercises used in NMT	13.9	14.5	0	8.5
Duration of NMT/min	13.9	17.5	0	15
Competition				
Adherence/%	23.2	16.7	0	0
No of exercises used in NMT	13.5	13.5	0	0
Duration of NMT/min	15.0	15	0	0
Subjective answers				
Is it possible to prevent PARI?	2.25		4	
Did PARI diminish?	4.0		3	
Does prevention matters?	4		3	
I will use NMT in the future	3		3.5	
Why NMT was not used?	Unavailable facilities		No time New coach Other prevention used	
Do you use other PARI prevention program?	75% yes		100% yes	

overall, training and match exposures, respectively. Moreover, IRR for sustaining an injury was 2.6 on average (ranging from 0.88 to 7.07 for tendon and muscle injuries, respectively), indicating significantly higher IRR in CG compared to IG (Table 4). The most common injuries such as ankle sprains were significantly reduced in IG compared to CG (IRR = 2.21, $p = 0.033$), while the relative risk for sustaining knee injuries was not (IRR = 0.88, $p = 0.108$). Furthermore, when only non-contact ankle sprains and knee injuries were considered, IG experienced lower risk of injury compared to CG. However, this observed difference did not reach statistical significance (ankle sprains, IRR = 1.99, $p = 0.090$; knee injuries, IRR = 2.06, $p = 0.142$) (Table 4).

4. Discussion

The aim of the present study was to evaluate the effects of a targeted NMT warm-up intervention program in adolescent basketball players during their training practice and competition on neuromuscular function; adherence, maintenance and acceptance of intervention; and injury incidence. The Td, in VL, GM and BF muscles, was different between groups, with a greater decrease (i.e., positive alterations) in the IG compared to the CG. The adherence to intervention was very high and moderate – achieving 91.1% and 60.2% during the intervention and follow-up period, respectively. Finally, the relative risk of injury was 2.15 times higher in the CG compared to the IG over the whole course of the study, including a follow-up period.

TMG-derived parameters provided insights into the effectiveness of the NMT warm-up program on the neuromuscular function. The similarities in most parameters between the two groups, particularly for Dm and Tc, may indicate that some neuromuscular adaptations occurred independently of the targeted training. These findings might be prescribed to the specificity of basketball specific training practice and movement patterns including high intensity drills such as sprinting, jumping sudden change of direction, and so on (Stojanović et al., 2018). However, the differences in Td among all assessed muscles, with a greater decrease in the IG, which was coupled with decreased Tc in GM, demonstrate the specific impact of the NMT on the onset of the muscle contraction and plantar flexor contraction time. Our findings are in line with previous research that aimed to investigate the alterations of TMG-derived parameters following exercise intervention. For example, Zubac and Šimunič (Zubac & Šimunič, 2017) reported decrease in VL, BF and GM Tc following 8-week plyometric training in young adults. Furthermore, these alterations highly correlated with the increase in countermovement jump height. This suggests that decreased Tc might be a result of plyometric exercise-induced changes in the muscle structure and function (Arntz et al., 2022). For example, Malisoux et al. (Malisoux et al., 2006) found that 8-week plyometric training increased the single-fibre cross-sectional area by + 23% in type I, +22% in type IIa, and + 30% in type IIa/IIx fibres, indicating a greater increase in fast-twitch muscle fibres and consequently greater power output and single fibre contraction velocity. On the other hand, the Td is less investigated in the literature, and a thorough comparison with the already published studies cannot be drawn. However, from the studies investigating the muscle activation patterns, we know that altered timing in the recruitment of individual quadriceps muscle heads may lead to an increased risk of ACL injuries (Hewett et al., 2005; Rocchi et al., 2018). A recent study found that delayed mediolateral quadriceps muscle activation timing during the drop fall test can identify athletes at the risk of injury (Marotta et al., 2020). Furthermore, to investigate the influence of a specific warm-up protocol on mitigating the pre-activation time in major knee stabilisation muscles, de Sire et al. (De Sire et al., 2021) compared NMT and standard warm-up protocols. The authors (De Sire et al., 2021) showed that NMT as a warm-up has an immediate positive effect on the pre-activation time of major knee stabilisation muscles in soccer players, namely, VM, RF and BF. While future studies should investigate the relationship between the onsets of muscle contraction derived from TMG and EMG, we may preliminarily conclude that our findings support the notion that targeted NMT as a warm-up can lead to unique muscle adaptations beneficial for injury prevention (De Sire et al., 2021).

In line with previous findings (Lindblom et al., 2012, 2020), we did not observe any significant effect of the NMT warm-up

Table 3. Changes in antrhopometry, Y-balance test, and tensiomyography-derived parameters between intervention and control groups following the intervention period.

	Intervention group		Control group		p_{GROUP}	p_{TIME}	$p_{TIME*GROUP}$
	BDC [95% CI]	POST [95% CI]	BDC [95% CI]	POST [95% CI]	[PE; SE]	[PE; SE]	[PE; SE]
Anthropometry							
Body height/cm	174.6 [172.7; 176.5]	176.0 [174.1; 178.0]	175.9 [174.1; 177.7]	176.6 [174.8; 178.4]	0.474[−0.56; 1.35]	<0.001[−0.72; 0.37]	0.137[−0.76; 0.51]
Body mass/kg	65.1 [62.5; 67.7]	64.0 [61.4; 66.6] *	64.4 [62.0; 66.8]	65.8 [63.3; 68.3] #	0.756[−1.81; 1.83]	0.682[−1.37; 0.41]	<0.001[2.51; 0.56]
BMI/kg/m^2	21.2 [20.7; 21.8]	20.5 [19.9; 21.1] #	20.5 [19.9; 21.0]	20.8 [20.2; 21.4]	0.542[−0.27; 0.42]	0.107[−0.30; 0.18]	<0.001[1.02; 0.26]
Fat mass/%	20.5 [19.4; 21.6]	16.4 [15.1; 17.6] #	14.6 [13.5; 15.6]	14.1 [12.9; 15.3]	<0.001[2.25; 0.88]	<0.001[0.49; 0.46]	<0.001[3.65; 0.69]
Y-balance test – normalized per leg length							
Anterior right/cm^2	72.9 [70.4; 75.4]	61.6 [58.9; 64.4]	69.2 [66.9; 71.5]	54.8 [52.2; 57.5]	0.002[6.76; 1.92]	<0.001[14.4; 1.13]	0.055[−3.06; 1.59]
Anterior left/cm^2	73.6 [71.3; 75.9]	71.8 [69.3; 74.3]	70.6 [68.4; 72.7]	66.7 [64.2; 69.1]	0.007[5.15; 1.78]	<0.001[3.88; 1.10]	0.169[−2.14; 1.55]
Posterior-medial right/cm^2	83.3 [80.9; 85.7]	84.0 [81.5; 86.6]	79.1 [76.9; 81.4]	78.1 [75.5; 80.6]	0.001[5.98; 1.86]	0.846[1.06; 1.17]	0.275[−1.80; 1.65]
Posterior-medial left/cm^2	82.6 [80.3; 84.9]	84.8 [82.3; 87.2]	78.0 [75.8; 80.1]	77.7 [75.2; 80.2]	<0.001 [7.09; 1.80]	0.262[0.30; 1.16]	0.138[−2.42; 1.62]
Posterior-lateral right/cm^2	84.1 [81.6; 86.6]	87.1 [84.4; 89.8]	81.2 [78.8; 83.6]	86.9 [84.2; 89.6]	0.352[0.20; 1.96]	<0.001[−5.68; 1.21]	0.114[2.68; 1.69]
Posterior lateral left/cm^2	85.0 [82.5; 87.5]	88.7 [86.1; 91.4]	82.7 [80.3; 85.0]	86.6 [84.0; 89.53]	0.178[2.09; 1.91]	<0.001[−3.99; 1.08]	0.849[0.29; 1.52]
Tensiomyography							
VL Td/ms	23.3 [23.0; 23.6]	22.9 [22.6; 23.2] *	22.2 [22.0; 22.5]	22.6 [22.3; 23.0] *	<0.001[0.24; 0.25]	0.933[−0.41; 0.19]	0.001[0.84; 0.26]
GM Td/ms	22.6 [22.3; 22.9]	22.3 [22.0; 22.7]	22.6 [22.3; 22.8]	23.6 [23.1; 24.0] #	0.005[−1.05; 0.27]	0.012[−0.92; 0.20]	<0.001[1.11; 0.27]
BF Td/ms	26.1 [25.7; 26.5]	25.9 [25.4; 26.4]	25.4 [25.0; 25.8]	26.2 [25.7; 26.8] $	0.594[−0.37; 0.37]	0.136[−0.80; 0.28]	0.007[1.04; 0.38]
VL Tc/ms	22.2 [21.8; 22.7]	22.7 [22.2; 23.1]	21.8 [21.4; 22.2]	22.5 [22.0; 22.9]	0.249[0.21; 0.34]	<0.001[−0.64; 0.23]	0.484[0.21; 0.30]
GM Tc/ms	22.6 [22.0; 23.2]	22.6 [22.0; 23.2]	22.7 [22.2; 23.3]	24.7 [24.0; 25.4] #	0.002[−2.13; 0.48]	<0.001[−1.98; 0.39]	<0.001[1.99; 0.53]
BF Tc/ms	30.0 [28.7; 31.3]	32.5 [31.0; 33.9]	31.3 [30.1; 32.6]	33.7 [32.2; 35.3]	0.125[−1.28; 1.08]	<0.001[−2.41 0.80]	0.982[−0.02; 1.08]
VL Dm/mm	5.80 [5.54; 6.05]	5.97 [5.70; 6.24]	5.58 [5.34; 5.82]	5.86 [5.57; 6.15]	0.351[0.11; 0.20]	0.008[−0.28; 0.13]	0.528[0.11; 0.17]
GM Dm/mm	3.02 [2.86; 3.19]	3.32 [3.14; 3.50]	3.41 [3.25; 3.56]	3.75 [3.56; 3.94]	<0.001[−0.43; 0.14]	<0.001[−0.34; 0.09]	0.761[0.04; 0.12]
BF Dm/mm	5.61 [5.23; 6.00]	6.66 [6.24; 7.08]	6.04 [5.67; 6.40]	6.87 [6.42; 7.32]	0.221[−0.21; 0.31]	<0.001[−0.83; 0.21]	0.441[−0.22; 0.28]
VL Vr/m/s	0.127 [0.121; 0.132]	0.131 [0.125; 0.137]	0.127 [0.122; 0.132]	0.130 [0.124; 0.136]	0.953[0.001; 0.004]	0.039[−0.003; 0.003]	0.733[−0.001; 0.004]
GM Vr/m/s	0.067 [0.064; 0.071]	0.074 [0.071; 0.078] *	0.075 [0.072; 0.079]	0.078 [0.074; 0.082]	0.011[−0.004; 0.003]	<0.001[−0.003; 0.002]	0.049[−0.004; 0.002]
BF Vr/m/s	0.099 [0.094; 0.105]	0.113 [0.107; 0.119]	0.106 [0.100; 0.111]	0.114 [0.107; 0.121]	0.358[−0.001; 0.005]	<0.001[−0.009; 0.003]	0.190[−0.005; 0.004]

*BDC – baseline data collection; 95% CI – 95% confidential interval of the mean; PE – parameter estimate; SE – standard error; decreased from BDC at: * $p < 0.05$; $ $p < 0.01$; # $p < 0.001$. VL – vastus lateralis; GM – gastrocnemius medialis; BF – biceps femoris; Td – delay time; Tc – contraction time; Dm – radial amplitude; Vr – radial velocity.*

Table 4. Physical activity related injuries.

	Intervention group		Control group			The whole study duration			
	Intervention period	Follow-up period	Intervention period	Follow-up period	RR	95% LCI	95% UCI		Decreased risk of injury in INT vs CON
No of injuries (prevalence)	13 (10.0%)	1 (0.8%)	21 (14.4%)	13 (8.9%)	2.15	1.38	3.33	0.001	−115%
Training	4	1	7	6	2.30	1.00	5.29	0.052	−130%
Competition	9	0	12	7	1.87	1.16	2.99	0.010	−87%
Contact	5	0	12	5	3.00	1.04	8.72	0.044	−200%
Non-contact	8	1	9	8	1.67	1.12	2.48	0.012	−67%
Upper body	2	0	4	3	3.09	0.54	17.87	0.208	−209%
Lower body	11	1	17	10	1.99	1.28	3.08	0.002	−99%
Sprains	8	0	13	4	1.88	1.13	3.12	0.016	−88%
Bone fracture	1	0	1	0	0.88	1.24	0.63	0.478	12%
Tendon	3	0	0	3	0.88	1.07	0.73	0.217	12%
Muscle	0	1	5	3	7.07	0.12	401.32	0.343	−607%
Ankle sprains/all	**6**	**0**	**11**	**4**	2.21	1.07	4.57	0.033	−121%
Ankle sprains/non-contact only	**4**	**0**	**4**	**5**	1.99	0.90	4.39	0.090	−99%
Knee injury	**5**	**0**	**2**	**3**	0.88	1.03	0.76	0.108	12%
Knee injury/non-contact only	**3**	**0**	**2**	**5**	2.06	0.79	5.40	0.142	−106%
Others	1	0	2	3	4.42	0.19	105.21	0.359	−342%

program on balance performance. Neuromuscular function plays a vital role in athletes' performance and injury risk (Brunner et al., 2019; Lutter et al., 2022; Stephenson et al., 2021). The observed improvement in neuromuscular function, as assessed by the Y-balance test, in both the CG and IG indicates that regular sports-specific training itself can enhance players' neuromuscular capabilities. While there were no differences between the groups, the overall improvement suggests that both groups benefited from their respective training regimens. This underscores the importance of incorporating neuromuscular exercises in regular training programs during a warm-up routine, even for healthy athletes, to optimize their physical function.

The NMT warm-up program used in the present study was incorporated as a specific warm-up routine with no more than 15 minutes in duration on average. Thus, it made it easier for coaches to accept the proposed NMT warm-up program while securing high athletes' adherence, i.e., 91.1% (Steffen, Meeuwisse, et al., 2013). Adherence to the NMT intervention is a crucial aspect of any preventive program (Steffen, Meeuwisse, et al., 2013). Higher adherence to prevention programs has been associated with lower risk of sports injuries in many randomized controlled trials (Hägglund et al., 2013; Soligard et al., 2010; Steffen, Emery, et al., 2013; Verhagen et al., 2011). Comparisons with previous studies are difficult to conduct considering the lack of existing studies in basketball players; however, Steffen, Emery, et al. (2013) observed adherence ranging from 78.2% to 87% on average, which is lower compared to our study (≥90%). Authors (Steffen, Emery, et al., 2013) concluded that higher adherence to the prevention program resulted in greater improvements in both balance and injury risk reduction in youth female football players. The high and moderate adherences achieved during in the current study (≥90%) indicate the feasibility and acceptability of the NMT intervention among adolescent basketball players. This finding is encouraging, as it suggests that young athletes are willing to engage in such programs and can maintain their commitment to injury prevention over time. Studies investigating NMT effectiveness in basketball players exclusively (Cumps et al., 2007; Eils et al., 2010; Longo et al., 2012; Riva et al., 2016; Stojanović et al., 2023) lack reporting of the adherence to intervention (Cumps et al., 2007; Eils et al., 2010; Longo et al., 2012), whereas Riva et al. (Riva et al., 2016) reported 100% adherence to a proprioceptive prevention program. Thus, our results are hard to compare to the existing literature examining the effectiveness of the preventive interventions within the basketball players in isolation. However, two previous meta-analyses have investigated the effects of exercise-based Injury Prevention Programs (IPP) adherence on the risk of sports injuries, and both have exclusively focused on ACL injuries (Halvorsen et al., 2023; Sugimoto et al., 2012). In a meta-analysis conducted by Sugimoto et al. (Sugimoto et al., 2012), which included female athletes (volleyball, soccer, basketball, and handball), a 4.9 times greater risk of ACL injury was observed in studies with low compliance (compliance < 33.3%) compared to those with high compliance (compliance > 66.6%). They demonstrated a 92% reduction in ACL injury risk in studies with high compliance, a 46% reduction in studies with moderate compliance (compliance 66.6%-33.3%), and a 12% reduction in studies with low compliance. In the most recent meta-analysis by Halvorsen et al. (Halvorsen et al., 2023) (which included a total of 15 articles, 11 of which were randomized controlled trials; football, soccer, basketball, volleyball, handball, floorball, and lacrosse), a 41% lower risk of ACL injury was reported overall with the use of IPP. High adherence levels (>75%) were associated with a significantly lower injury rate of 64%, while the moderate adherence group (51–75%) showed a risk reduction of 35% and the low adherence group (<50%) showed a 28% risk reduction (Halvorsen et al., 2023). These findings suggest laying strong evidence that adherence is vital for sustaining the benefits of the intervention and ensuring its long-term effectiveness.

The relative risk of injury being 2.15 times higher in the CG compared to the IG highlights the protective effect of the prescribed NMT warm-up program. This suggests that the intervention had a substantial impact on reducing the risk of injuries occurring during the entire study duration as well as during the follow-up period. In line with the findings of Stojanović et al. (2023), we observed substantial effect not only on ankle sprains but on knee injuries as well. These findings are of great value since as we mentioned previously, the research on NMT warm-up programs in youth basketball is sparse (Räisänen et al., 2021). It seems that by incorporating a targeted NMT warm-up program into regular practice and competition settings of adolescent basketball players, it is possible to significantly decrease injury incidence. Coaches and other sports professionals can utilize the results of this study to design evidence-based injury prevention programs tailored to the specific needs of their athletes. Such programs can focus on enhancing the neuromuscular function, improving muscle responsiveness, and optimizing movement control. By doing so, the risk of injury can be effectively mitigated, leading to healthier and more resilient athletes.

Finally, it is essential to recognize some limitations of the current study. While the findings are promising, the study's specific scope and population should be considered when extrapolating the results to other settings, female basketball players or sports. Furthermore, future research is needed to investigate the long-term effects of such interventions and explore the potential variations in responses across different age groups, skill levels, sports disciplines and among female basketball players.

5. Conclusion

In conclusion, the present study provides valuable insights into the effectiveness of a targeted NMT warm-up intervention program in preventing physical activity-related injuries in male adolescent basketball players. The reduction in injury risk of both ankle sprains and knee injuries and both upper and lower body injuries, along with the improvements in neuromuscular function, underscores the importance of implementing evidence-based injury prevention strategies in youth sports. By incorporating targeted NMT into regular training practice and competition, coaches and sports medicine professionals can foster healthier and more resilient young athletes, ultimately contributing to their long-term success and well-being in basketball and beyond.

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ORCID

Armin H. Paravlic http://orcid.org/0000-0002-7748-8097
Peter Bakalár http://orcid.org/0000-0001-6719-3618
Boštjan Šimunič http://orcid.org/0000-0003-1565-7833

Authors' contribution

Conceptualization, BŠ, PB; methodology, BŠ; formal analysis, BŠ, AP; investigation, BŠ, SP, MK, KT, KP, LS, MP, UM; resources, PB; data curation, BŠ and AP; data collection; SP, MK, KT, KP, LS, MP, UM; writing–original draft preparation, AP; writing–review and editing, AP, BŠ, PB; SP, MK, KT, KP, LS, MP, UM; project administration, BŠ.; funding acquisition, PB. All authors have read and agreed to the published version of the manuscript.

Reprint requests to Armin Paravlić

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