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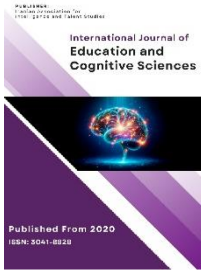

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The Effect of an Online Injury Prevention Warm-Up Program on Selected Physical Fitness and Performance Factors in School Students Aged 14 to 16

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ABSTRACT

Purpose: This study evaluated the effect of a six-week online injury prevention warm-up program on selected physical fitness and performance factors in school students aged 14 to 16.

Methods and Materials: A total of 344 students (172 girls, mean age = 15.3 years; 172 boys, mean age = 15.0 years) enrolled in physical education classes were randomly assigned to either a control group (n = 86) or an experimental group (n = 86). The intervention targeted four outcome variables: static balance, dynamic balance, flexibility, and agility. Pre- and post-intervention assessments were conducted over six weeks. Data were analyzed using independent t-tests and the Mann–Whitney U test.

Results: In boys, average percentage changes were as follows: static balance increased by 4.56%, dynamic balance by 1.12%, and flexibility by 5.07%, while agility decreased by 1.68%. In girls, static balance improved by 32.80%, dynamic balance by 1.21%, flexibility by 8.37%, and agility improved by 0.93%. Significant improvements were observed in dynamic balance and flexibility for both sexes, while agility significantly improved in girls and decreased in boys. Static balance significantly improved only in girls.

Conclusion: The findings demonstrate that a structured, online injury prevention warm-up program is effective in enhancing several key aspects of physical fitness and performance in adolescents, particularly in girls. The program can be implemented as an accessible and practical intervention in physical education settings to improve student outcomes and reduce injury risk.

Keywords: *Online warm-up, injury prevention, physical fitness, school students, agility, balance, flexibility.*

1. Introduction

In recent years, the significance of injury prevention and physical preparedness among adolescents has received increasing attention in physical education and sports science. Adolescents between the ages of 14 to 16 are particularly vulnerable to sports-related injuries due to rapid physical development, increased participation in school sports, and insufficient physical conditioning or warm-up practices prior to exercise. Properly designed injury prevention warm-up programs have been shown to significantly enhance motor performance, reduce the risk of musculoskeletal injuries, and support long-term athletic development (LaBella et al., 2011; Pasanen et al., 2009). With the increasing integration of digital technology into educational and training settings, the feasibility of delivering structured warm-up routines through online platforms presents a novel opportunity for large-scale injury prevention, especially in situations such as the COVID-19 pandemic, where remote instruction became essential (Richmond et al., 2016; Xu et al., 2023).

The physiological basis of warm-up programs lies in their ability to increase blood flow, elevate core and muscle temperature, improve joint mobility, and stimulate the nervous system for optimal muscle coordination and reaction time (Fradkin et al., 2010; Perrier et al., 2011). Numerous studies have confirmed that dynamic warm-up routines—particularly those emphasizing neuromuscular activation, proprioception, and agility drills—can significantly improve physical performance and reduce injury incidence in youth sports (Aguilar et al., 2012; Daneshjoo et al., 2012a; Wang & Pei, 2024). For instance, the well-established FIFA 11+ program, developed as a comprehensive injury prevention intervention, demonstrated notable improvements in strength, balance, and coordination in adolescent male athletes when implemented consistently (Brito et al., 2010; Zarei et al., 2018).

However, despite evidence supporting structured warm-up interventions, the implementation of such programs in school-based physical education remains inconsistent. Many school curricula still rely on outdated or insufficient warm-up practices that fail to address biomechanical vulnerabilities in adolescents or do not engage students adequately in preventive movement patterns (Mengxin, 2019; Talley, 2016). Furthermore, the reliance on in-person instruction has posed limitations in contexts where students cannot physically attend school due to health or logistical reasons. To address this, the emergence of virtual and hybrid learning environments in physical education offers promising pathways for structured injury prevention content delivery (Almusawi et al., 2021; Cui et al., 2023).

The effectiveness of online injury prevention programs, however, is contingent upon several pedagogical and physiological factors. These include the quality of content delivery, student engagement with exercises, and the adherence to evidence-based movement protocols. The integration of biomechanics and machine learning in some recent interventions has further underscored the potential of digital solutions in customizing injury prevention strategies and tracking movement quality in real time (Wang & Pei, 2024). In this context, school-based interventions delivered via virtual platforms can be designed not only to replicate but also to enhance traditional warm-up practices when aligned with scientific principles.

Research suggests that adolescents benefit most from warm-up interventions that incorporate components such as dynamic mobility, balance drills, core strengthening, and plyometric exercises, all of which are aimed at improving proprioception, reducing joint loading, and enhancing neuromuscular control (Aguilar et al., 2012; Daneshjoo et al., 2012b; Polavarapu, 2024). The cumulative effect of these components contributes to improved postural control and movement efficiency, which are critical in preventing injuries associated with sudden changes in direction, deceleration, and repetitive loading common in school sports (Gribble et al., 2012; Jo et al., 2011). Particularly, studies have shown that improvements in dynamic balance and flexibility are strong predictors of reduced injury risk in adolescent athletes (Hrysomallis, 2011; Miller et al., 2017).

Moreover, several school-based studies have emphasized the broader benefits of structured physical activity on student health outcomes beyond injury prevention. For example, the MOVI-KIDS study conducted in Spain demonstrated that school-based physical activity interventions can effectively reduce adiposity, improve cardiovascular fitness, and lower blood pressure in children (Martínez-Vizcaíno et al., 2020). Such findings underscore the dual role of preventive physical education programs in supporting both performance and public health goals. In parallel, the incorporation of digital health interventions in school settings has been gaining momentum, with platforms offering tailored feedback and behavioral monitoring to enhance the impact of traditional physical education (Xu et al., 2023).

Despite these advances, there remains a paucity of research focused specifically on the application of online

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warm-up programs within the context of injury prevention for secondary school students. Most prior studies have either focused on athletes in club sports or examined warm-up routines in controlled laboratory settings, thereby limiting the ecological validity of findings in everyday school environments (LaBella et al., 2011; Richmond et al., 2016). Furthermore, gender-specific responses to warm-up interventions have been understudied. Emerging evidence suggests that girls may exhibit greater gains in balance and flexibility metrics, while boys may respond more to agility-focused training, emphasizing the need for sex-sensitive designs in school-based warm-up programs (Miller et al., 2017; Zarei et al., 2018).

Given this background, there is a clear need to design and evaluate online injury prevention warm-up programs that are both scientifically grounded and practically feasible in school environments. The study presented here addresses this gap by examining the effects of a six-week online injury prevention warm-up intervention on selected physical fitness indicators—namely, static balance, dynamic balance, flexibility, and agility—among male and female secondary school students aged 14 to 16. The intervention is based on evidence-supported practices drawn from existing literature, particularly the structural components of FIFA 11+, neuromuscular activation drills, and school-appropriate dynamic movement patterns (Brito et al., 2010; Di Domenico & D'Isanto, 2019; Pasanen et al., 2009).

In alignment with studies demonstrating the validity and reliability of physical fitness tests used in youth populations, this research applies the Y-Balance Test to assess dynamic postural control, the modified sit-and-reach test for flexibility, and standardized agility tests such as the Illinois Agility Test, which have been previously validated for use in similar age groups (Esposito et al., 2019; Gribble et al., 2012; Perrier et al., 2011). The selected assessment tools not only ensure objective measurement of performance outcomes but also allow comparisons with existing data across international contexts.

Another dimension of relevance in this research is the growing emphasis on personalized and adaptive learning in physical education. As argued by Turnagöl et al., nutritional, biomechanical, and educational strategies must converge to offer individualized pathways for injury prevention and recovery (Turnagöl et al., 2021). In the context of digital learning environments, such personalization can be facilitated through wearable technology, real-time feedback systems, and adaptive exercise modules (Almusawi et al., 2021; Cui et al., 2023). While this study does not employ such devices, it sets the groundwork for future research that could incorporate machine learning-based analysis of biomechanical features during online warm-up sessions (Wang & Pei, 2024).

Furthermore, school physical education settings remain essential spaces for shaping lifelong health behaviors. Therefore, embedding injury prevention protocols within the school curriculum can have long-term benefits not only for sports participation but also for functional movement literacy, self-efficacy, and injury awareness among adolescents (Polavarapu, 2024). As pointed out by Richmond et al., school-based programs also offer logistical advantages in terms of scalability, standardization, and inclusivity, making them ideal platforms for widespread dissemination of evidence-based injury prevention strategies (Richmond et al., 2016).

In summary, this study contributes to the evolving body of literature on physical education, injury prevention, and digital intervention by testing a structured, online warm-up program tailored for adolescents in a school setting.

2. Methods and Materials

2.1. Study Design and Participants

This study employed a practical, quantitative, and quasi-experimental design. Students were randomly assigned to study groups at the school level. Two secondary schools (one for girls and one for boys) in Tehran with structured physical education programs were selected. Within each school, students were randomly divided into experimental and control groups.

The sample comprised students from grades 10, 11, and 12 attending two public high schools (one boys' and one girls') in District 14 of Tehran. Physical education classes were held once per week for 90 minutes, and no additional sessions were scheduled for the study. Using G*Power software ($\alpha = 0.05$, effect size = 0.8, power = 0.95), the required sample size was calculated to be 344 students—172 girls and 172 boys—who were randomly assigned to either control or experimental groups ($n = 86$ per group).

Research variables were categorized into independent and dependent types. The dependent variables included static balance, dynamic balance, flexibility, and agility. Inclusion criteria were: age between 14 and 16, regular attendance in school PE classes, no membership in sports clubs during the study, no prior participation in injury prevention programs, and no history of relevant medical conditions (e.g., anesthesia, vertigo, musculoskeletal

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disorders, systemic disease, or surgery). Exclusion criteria included the onset of pain during testing that prevented participation, lack of informed consent from students or their parents, and failure to complete both pre- and post-tests.

2.2. Measures

To assess flexibility, the Modified Sit-and-Reach Test was used, a standard field test of hamstring and lower back flexibility (Baltaci et al., 2003; Lemmink et al., 2003). Participants sat on the floor with their backs against a wall, legs extended and feet pressed flat against a test box. With hands placed one over the other and back and head against the wall, participants extended their hands forward along the box as far as possible, holding the stretch for two seconds. The maximum reach was recorded.

Agility was assessed using the Illinois Agility Test, which required participants to navigate a course marked by eight cones. Side cones were spaced 10 meters apart, and each side cone was 5 meters from the center cones, which were spaced 3.5 meters apart. On the teacher's signal, participants completed the course as quickly as possible, changing direction according to the course design (Esposito et al., 2019; Reilly et al., 2000).

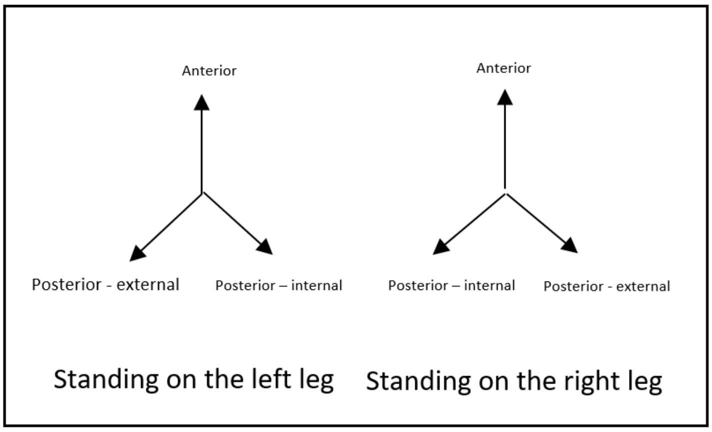
Static balance was measured using the One-Leg Standing Test, widely applied in athletic assessments (Jo et al., 2011). The dominant leg (defined as the preferred leg for kicking a ball) was identified for each participant. Participants stood with hands on their hips, lifted one leg to rest its toes on the opposite knee, and then rose onto the toes of the supporting leg. Time was recorded from lift-off until balance was lost.

Dynamic balance was evaluated using the Y-Balance Test, derived from the Star Excursion Balance Test and validated by Gribble (Gribble et al., 2012). This test measures balance in three directions—anterior, posteromedial, and posterolateral—arranged in a Y-shape at 135°, 135°, and 90°, respectively. Each participant performed four practice trials to familiarize themselves with the task. The test was performed in a clockwise direction for those with a left dominant leg, and counter-clockwise for those with a right dominant leg. In each direction, the reach distance (in cm) was recorded and normalized as a percentage of leg length. The average of three trials per direction was calculated, and a composite score was derived by averaging the three normalized distances (Plisky et al., 2009).

Physical measurements were taken before and after the 6-week intervention. These included height, weight, and leg length. Height was measured using a tape measure with the participant standing barefoot and looking straight ahead. Leg length was measured from the hip to the medial ankle. Weight was measured using a Sahand digital scale (accuracy = 0.001 kg) with participants barefoot and wearing light clothing. Body Mass Index (BMI) was then calculated.

Figure 1

Dynamic balance test



2.3. Intervention

The intervention was delivered via an online virtual learning platform under standardized conditions at both schools. The six-week program included one 70-minute session per week, conducted in six groups of approximately 25 students each (3 experimental, 3 control).

In the experimental group, students performed a structured injury prevention warm-up routine, while the control group followed a traditional warm-up. Both groups

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then engaged in rope jumping and step aerobics, followed by a cool-down. To support home practice, a 10-minute instructional video on the injury prevention warm-up was uploaded to the schools' learning management systems. Students were asked to rehearse the exercises at home prior to each weekly class.

At the start of each PE session, the experimental group performed the injury prevention warm-up for 15 minutes, while the control group completed a standard warm-up. Both warm-ups were based on a protocol adapted from Richmond et al. (Richmond et al., 2016). The injury prevention program consisted of three components: running (10 minutes), balance training (5 minutes), and strength exercises (5 minutes). The entire session was monitored live via webcam, due to COVID-19 restrictions.

Figure 2

Injury Prevention Warm-Up Program

AEROBIC COMPONENTS

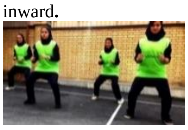
1. FORWARD RUN – 2 laps around the gym. Progressing speed on the 2nd lap.

2. FORWARD RUNING, WITH SKIPPING knees aligned over the ankles, and lightly landing on toes.

3.FORWARD RUNING ,WITH KNEE LIFTS
Landing lightly on the toes with correct alignment of the knee over the ankle on landing and not allowing the knee to buckle inward.

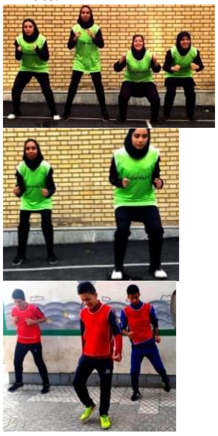
4.FORWARD RUNNING, WITH HEEL KICKS
Alternating heels touch the buttocks, without flexing at the hip. Focus on landing lightly on the toes while keeping the knee aligned over the ankle

5.SIDEWAY SHUFFLES
Knees over the ankles, not allowing the knees to buckle inward.



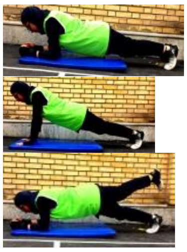
6.ZIGZAG RUNNING
Knees are constantly bent; with correct alignment over the center of the ankle; not allowing the knee to fall inward. Progress to a faster plant and cut manoeuvre, ensuring the planting knee is aligned over the ankle. Further progression is to complete the shuffle (see component 5) in a sig zag formation.

9.jumping
1) two legged squad jumps
Soft landing on toes, take off and landing with hips and knees bent, maintaining knee over ankle alignment, avoiding knees buckling inward and gently engaging abdominal muscles.
2) two legged squad jumps over a line
Progression to this exercise includes moving forward/backward or side-to-side over a line. Avoiding the knees buckling inward or advancing too far forward.
3) skate jump
Focus is on a soft landing on the toes, absorbing weight, lowering the heel to the floor and maintaining knee over ankle alignment while avoiding knees buckling inward. Repeat this exercise for 30 seconds to begin and progress to 1 minute.



BALANCE COMPONENTS

10. WOBBLE BOARD
1) two foot balance
Stand with both feet on the wobble board. Body weight should be evenly distributed with the chest forward, hips back, and knees apart, slightly bent and aligned over the ankle. Maintain balance, with the wobble board surface flat, for as long as possible.
2) two-foot balance with ball activities
Progress to two-foot balance with ball activities, such as tossing between partners or dribbling.
3) two-foot balance with partner perturbations
Progress to a two-foot balance with partner perturbations by slightly nudging a partner with one or two fingers.



12.SIDE PLANK
1)side plank on elbows
Maintain the body in a straight line from head to toe. Elbow of the supporting forearm is positioned under the shoulder. Hold for 20-30 seconds, and repeat 3 times on each side of the body. Progress to hold longer than 30 seconds.
2)side plank on hands
Place hand under the shoulder and raise the body, while maintaining a straight body position from head to toes. Further progression can be completed with slow and controlled leg lifts during side plank on elbows, then progress further to side plank on the hands.

13.HAMSTRINGS
Maintain a straight line from head to knees. Slowly lower the body toward the mat, keeping the head, shoulders, hips, and knees in a straight line. Repeat 3 times and progress to 10 repetitions. Progress by achieving a position closer to the mat and holding it longer.

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7.FORWARD RUNNINGWITH INTERMITTENT STOPS

Stop in a controlled position, with the knees in the correct alignment over the ankles.

8. SPEED RUNS

Running fast while maintaining correct running form and using the arms to support the movement.

STRENGTHENING COMPONENTS

11.PLANK

1) plank on elbows

Maintain the body in a straight line from head to toes. Elbows are positioned under the shoulders and chin slightly tucked in. hold for 20-30 seconds, and repeat 3 times. Progress to hold longer than 30 seconds.

2)plank on hands

Progression to this exercise is to place hands on the floor under the shoulders instead of the elbows.

3)plank with alternating leg lifts

Focus on correct plank position while a small leg lift is completed in a slow and controlled manner. Complete first while in plank on the elbows, then further progress to plank on the hands. Repeat 3 times on both legs initially, and progress to 10 repetitions.

14.LUNGES

1) Static lunges

Bend the front knee to a 90 degree angle. Focus should be on a slow, controlled movement lowering into the lunge, ensuring correct knee alignment over the ankle; not allowing the knee to buckle inward.

2) walking lunges

Progress to walking lunges, whereby from the lunge position, the back foot is brought directly from behind to the lead, and the front foot now lowers towards the ground and becomes the back foot.

Figure 3 Injury Prevention Warm up Program

2.4. Data Analysis

The data analysis in this study was conducted using both descriptive and inferential statistical methods. Descriptive statistics, including means and standard deviations, were used to summarize demographic variables and pre- and post-test performance scores. The Kolmogorov–Smirnov test was applied to assess the normality of data distribution for each variable. Due to violations of normality assumptions for several variables, non-parametric tests were employed where appropriate. Specifically, the Mann–Whitney U test (also referred to as the Yeoman–Whitney test) was used to compare percentage changes in static balance, dynamic balance, and flexibility between control and experimental groups. For the agility variable, which followed a normal distribution, independent t-tests were used to analyze between-group differences. All statistical analyses were performed using SPSS software version 26, with a significance level set at $p < 0.05$.

3. Findings and Results

In the descriptive analysis, frequency, mean, and standard deviation were used to summarize the demographic and research variables. In the inferential analysis, due to the violation of ANOVA assumptions, independent t-tests and Mann–Whitney U tests were used to compare the percentage changes in dependent variables between the experimental and control groups from pre-test to post-test. Normality of data distribution was assessed using the Kolmogorov–Smirnov test.

For within-group comparisons (boys and girls, experimental vs. control), the agility variable exhibited a normal distribution; therefore, independent t-tests were applied. For the variables of static balance, dynamic balance, and flexibility, which did not meet the assumption of normality, the Mann–Whitney U test was used.

Descriptive statistics for demographic characteristics by gender are presented in Table 1.

Table 1

Demographic Characteristics of Participants

Variable	Girls (M ± SD)	Boys (M ± SD)
Age (years)	15.30 ± 0.00	15.00 ± 0.07
Weight (kg)	56.68 ± 3.53	71.81 ± 28.99
Height (m)	1.63 ± 0.09	1.76 ± 0.00
BMI (kg/m²)	20.89 ± 3.22	23.15 ± 8.20

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Table 2 reports the average percentage changes in the dependent variables (post-test − pre-test ÷ pre-test × 100) for each group.

In the **boys' group**:

- **Static balance**: The Mann–Whitney U test indicated no significant difference between experimental and control groups (P = 0.387, U = 3415.000). However, the experimental group showed a 4.56% increase.
- **Dynamic balance**: A significant difference was observed (P < 0.001, U = 2197.000), with a 1.12% increase.
- **Flexibility**: A significant difference was found (P = 0.006, U = 2808.500), with a 5.07% improvement.
- **Agility**: The independent t-test showed a significant difference (P < 0.001, t(169.35) = 4.09). The agility score decreased by 1.68%, indicating improvement in time.

In the **girls' group**:

- **Static balance**: No significant difference was observed (P = 0.918, U = 3706.000); however, the percentage change increased by 32.80%.
- **Dynamic balance**: The test revealed a significant difference (P < 0.001, U = 2458.500), with a 1.21% improvement.
- **Flexibility**: A significant difference was found (P = 0.001, U = 2615.500), with an 8.37% increase.
- **Agility**: The t-test indicated a significant difference (P = 0.041, t(171) = 2.059), with a 0.93% improvement.

In comparing **boys and girls**:

- For **static balance**, a significant difference was found between the two groups (P < 0.001, U = 2583.000).
- For **dynamic balance**, no significant difference was observed (P = 0.173, U = 3253.000).
- For **flexibility**, the t-test revealed no significant difference (P = 0.071, t(95.74) = 1.824).
- For **agility**, a significant difference was found (P < 0.001, t(97.86) = −4.414).

Table 2

Comparison of Pre-Test and Post-Test Results Between Control and Experimental Groups (M ± SD)

Variable	Group	Girls (Pre)	Girls (Post)	Boys (Pre)	Boys (Post)	P (G×B)	P (C×E)
Static Balance	Control	2.39 ± 5.19	2.62 ± 6.11	2.96 ± 5.85	2.95 ± 6.05	<0.001	0.918
	Experimental	3.85 ± 6.30	4.55 ± 7.50	2.87 ± 5.68	2.88 ± 5.84		0.387
Dynamic Balance	Control	14.11 ± 82.64	14.46 ± 82.41	10.46 ± 77.80	12.56 ± 76.97	0.173	<0.001
	Experimental	14.93 ± 83.66	15.81 ± 84.36	11.50 ± 78.98	18.17 ± 76.84		<0.001
Flexibility	Control	2.09 ± 18.80	2.30 ± 19.26	9.26 ± 22.78	9.84 ± 21.68	0.071	0.001
	Experimental	2.20 ± 19.50	2.31 ± 19.68	8.40 ± 22.51	8.53 ± 23.06		0.006
Agility	Control	8.63 ± 21.95	8.79 ± 21.29	1.86 ± 19.14	1.92 ± 19.39	<0.001	0.041
	Experimental	8.94 ± 25.00	9.18 ± 26.31	1.65 ± 18.76	1.86 ± 18.45		<0.001

The protocol was systematically structured to support adolescents in developing self-awareness, emotional regulation, and kindness toward themselves in a supportive peer environment. In the first session, a safe and trusting group dynamic was established, laying the foundation for the emotional work ahead. Session 2 built on this by helping adolescents become more literate in recognizing and labeling their emotional experiences, a crucial first step in interrupting harmful behavior cycles. In Session 3, the focus shifted to accepting difficult emotions rather than avoiding or suppressing them—participants practiced observing feelings with openness and without judgment.

Session 4 addressed the pervasive issue of self-criticism. Through cognitive-behavioral techniques and guided meditations, adolescents learned to identify harsh inner dialogue and replace it with a nurturing inner voice. In Session 5, the focus moved toward cultivating mindfulness in everyday life. Practical exercises helped participants anchor their awareness in the present moment and observe thoughts non-reactively, an important skill for distress tolerance.

In Session 6, safe and constructive emotional expression was encouraged through storytelling and art-based modalities, allowing adolescents to externalize their inner pain without resorting to self-harm. Session 7 built interpersonal resilience by fostering compassionate connections and modeling how to seek help effectively. Session 8 introduced value-based living, encouraging participants to identify deeper meanings and motivations beyond self-destructive behavior.

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In Session 9, adolescents integrated their learnings to begin constructing a new, compassionate sense of self that acknowledges suffering without being defined by it. The final session (Session 10) focused on relapse prevention strategies, consolidating gains, and reinforcing the sense of closure, empowerment, and mutual support within the group.

Each session was carefully sequenced to build upon the previous ones, allowing for gradual but meaningful transformation rooted in participants' lived experiences. This evidence-informed and experience-driven protocol is designed to be replicable, developmentally appropriate, and sensitive to the psychological needs of self-injuring adolescents.

To ensure the scientific robustness of the designed mindful self-compassion protocol, content validity and reliability were assessed using three standard indices: Content Validity Ratio (CVR), Content Validity Index (CVI), and the Kappa coefficient. A panel of 12 experts in clinical psychology, adolescent mental health, and curriculum design independently reviewed each session objective, activity, and assigned home practice. They evaluated each item based on relevance, clarity, and necessity. For CVR, experts rated whether each item was "essential," "useful but not essential," or "not necessary." For CVI, they assessed relevance on a 4-point Likert scale. Kappa was calculated to correct for chance agreement among experts in CVI assessments.

4. Discussion and Conclusion

This study investigated the effect of a six-week online injury prevention warm-up program on selected physical fitness factors—namely, static balance, dynamic balance, flexibility, and agility—in secondary school students aged 14 to 16. The results revealed significant improvements in the physical performance of the experimental group compared to the control group, particularly in measures of flexibility, agility, and dynamic balance. The intervention's effect varied across gender, with female participants showing more pronounced gains in balance and flexibility metrics. These findings align with a growing body of evidence supporting the efficacy of structured warm-up protocols in enhancing performance and reducing injury risk among adolescents in educational settings.

One of the notable findings was the improvement in static balance, especially among girls in the experimental group, who demonstrated a 32.8% increase. Although this change was not statistically significant when comparing experimental and control groups directly, the magnitude of improvement is consistent with previous studies showing enhanced postural control following neuromuscular warm-up routines. For instance, neuromuscular training programs have been shown to improve proprioceptive mechanisms and muscular coordination, thereby enhancing balance performance in youth populations (Daneshjoo et al., 2012b; Gribble et al., 2012). The difference in outcomes between girls and boys may be attributed to neuromuscular and anatomical differences as well as gender-specific responsiveness to proprioceptive training (Miller et al., 2017). Similar to findings by Pasanen et al., warm-up routines that integrate balance and strength components improve postural control more significantly among female athletes (Pasanen et al., 2009).

The results for dynamic balance were also significant. Both girls and boys in the experimental group showed improvements, with boys exhibiting an 18.17% post-test score compared to 12.56% in the control group. The dynamic balance results are particularly relevant because deficits in dynamic postural control are strongly associated with lower-extremity injuries in adolescent athletes (Gribble et al., 2012; Plisky et al., 2009). These results reaffirm the value of including balance-specific drills such as the Y-Balance test components in injury prevention protocols (Jo et al., 2011). The online delivery of such exercises did not appear to diminish their efficacy, highlighting the adaptability of proprioceptive training to digital platforms. Similar findings have been documented in hybrid intervention models, where virtual physical education successfully enhanced lower-limb stability and motor performance (Cui et al., 2023; Xu et al., 2023).

Regarding flexibility, both groups demonstrated improvements, though the experimental group achieved statistically significant gains—5.07% in boys and 8.37% in girls. These findings are in agreement with past studies confirming that dynamic stretching exercises, such as lunges and leg swings, improve hamstring flexibility and hip joint range of motion when consistently applied during warm-ups (Aguilar et al., 2012; Perrier et al., 2011). Warm-up protocols that include movement-based stretches are more effective than static stretching alone, especially for pre-activity preparation (Fradkin et al., 2010). The gains observed in this study are likely due to the inclusion of progressive stretching components, which stimulate the muscle–tendon unit and reduce passive resistance, thereby

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enhancing the range of motion and decreasing injury susceptibility (Talley, 2016).

Agility, as measured by performance in the Illinois Agility Test, also improved significantly in the experimental group, with boys improving by 1.68% and girls by 0.93%. This finding supports previous research demonstrating that agility performance can be enhanced through neuromuscular and dynamic warm-up routines that involve multidirectional movements and high-speed execution (Di Domenico & D'Isanto, 2019; Esposito et al., 2019). The 11+ program, which informed the structure of this intervention, similarly led to improved agility and speed in adolescent athletes after consistent application over a training cycle (Zarei et al., 2018). Improvements in agility are especially meaningful in adolescent populations where coordination, reaction time, and muscle power are still developing. They also contribute significantly to sports performance and overall injury resilience.

Importantly, the gender-based comparison revealed a statistically significant difference in agility between boys and girls, with boys showing greater improvement. This finding aligns with known physiological differences in neuromuscular development during adolescence. Male students, generally exhibiting higher baseline levels of muscle strength and anaerobic capacity, tend to respond more readily to speed and agility-focused training (Miller et al., 2017). However, it is also noteworthy that girls demonstrated greater relative improvements in flexibility and balance, suggesting that warm-up protocols should be tailored to gender-specific needs and physiological responsiveness for optimal results.

The effectiveness of online delivery was another key contribution of this study. Despite the physical distancing constraints imposed by the COVID-19 pandemic, the structured program was successfully implemented through the schools' virtual platforms. Students were able to follow guided instructional videos and participate in real-time sessions monitored by educators. Previous studies have reported similar outcomes from school-based injury prevention programs, demonstrating their scalability and practicality in diverse educational contexts (LaBella et al., 2011; Richmond et al., 2016). What distinguishes this study is the virtual nature of the intervention, reflecting how digital pedagogy in physical education can be as effective as in-person formats when supported by appropriate instructional design and engagement strategies (Almusawi et al., 2021).

In addition to improvements in physical performance metrics, the study reflects broader trends in integrating technology into physical education. The use of digital learning management systems, coupled with structured video-based instruction, represents an innovative model for delivering health and fitness curricula (Cui et al., 2023; Xu et al., 2023). Machine learning-based biomechanics applications, as explored by Wang and Pei, may further enhance this model by enabling real-time feedback on movement patterns, thereby improving the quality of at-home practice and reducing technique-related errors (Wang & Pei, 2024). While such tools were not implemented in the present study, their future inclusion could augment the effectiveness and individualization of online injury prevention programs.

This study also affirms the notion that injury prevention and performance enhancement are not mutually exclusive, but rather complementary outcomes of a well-structured warm-up protocol. Integrating core strengthening, balance drills, and functional mobility into a single routine, as recommended by previous authors (Brito et al., 2010; Daneshjoo et al., 2012a), produces measurable gains across multiple domains of fitness. Furthermore, the adaptability of such programs to the school setting underscores their potential for inclusion in national physical education standards, as advocated by recent systematic reviews of school-based interventions (Martínez-Vizcaíno et al., 2020).

While the study yielded promising results, it is not without limitations. First, the duration of the intervention—six weeks—may not have been sufficient to observe long-term effects or injury incidence reduction. Future studies could extend the program over an entire semester or academic year. Second, although the program was delivered online, adherence and engagement outside the live sessions were based on self-report and teacher observation, which could introduce bias. Additionally, the study focused solely on adolescents in Tehran and may not be generalizable to other cultural or educational contexts without adaptation. The lack of physiological measures (e.g., heart rate, muscle activation) also limits insights into the mechanisms driving performance gains.

Future investigations should explore the integration of wearable technology and real-time motion analysis to enhance feedback and engagement in online warm-up interventions. Researchers could also examine long-term retention of improvements and actual injury rates during school sport seasons. Comparative studies involving different age groups, cultural backgrounds, or types of physical activities would provide further insights into the program's generalizability and efficacy. Moreover, a deeper

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exploration into gender-specific responses using mixed-methods approaches may help tailor interventions more effectively.

Physical education instructors are encouraged to incorporate structured warm-up routines with components of dynamic mobility, balance training, and strength exercises into their regular curricula. Even in online or hybrid settings, these routines can be delivered effectively using digital tools and video resources. Schools should prioritize the training of PE teachers in evidence-based injury prevention protocols to ensure proper implementation. Given the positive outcomes observed, education policymakers should consider embedding such programs into national physical activity guidelines for adolescents.

Authors' Contributions

All authors significantly contributed to this study.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

In this study, to observe ethical considerations, participants were informed about the goals and importance of the research before the start of the interview and participated in the research with informed consent.

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