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RESEARCH

Lower Limb Dynamic Strength and Short Distance Locomotion Speed in 8-13 Year Old Female Ice Figure Skaters: Age Changes and Latent Factors

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Abstract
The aim of this study was to investigate age-related changes in leg muscle strength through a set of jumping and running and skating acceleration tests in young female ice figure skaters and to identify latent factors of performance in these tests. Standing long jump (SLJ), single-leg triple hop on the right leg (TJR) and left leg (TJL), repeated vertical jumps (RVJ), and 15 m skating and running acceleration on an ergometry device were measured in 437 female figure skaters aged 8–13 years. One-way MANOVA/ANOVA ($\alpha = 0.05$) showed progressive changes in all eleven indicators of the five tests, except for the ground contact time in RVJ. Performance in tests involving the horizontal component of force (SLJ, TJR, and TLJ) showed significant year by year improvements, while performance in other tests showed rather nonlinear changes with age. The results of principal component analysis with varimax rotation revealed three significant latent factors, i.e., the three functional qualities which were interpreted as follows: (i) the fast stretch–shortening cycle (SSC) capability for jumping in the vertical direction, determined by mechanical power (W/kg) during take-offs; (ii) the slow SSC capability for jumping in the horizontal direction, indicated by distance covered with TJR or TJL; and (iii) the fast SSC capability for skating, indicated by 15-m skating and running acceleration time.

Keywords Muscle strength · Stretch–shortening cycle · Lower extremity · Age variation · Girls

Introduction

Ice figure skating is a sport that requires a combination of grace, artistry, flexibility, speed, and power [51] while performing specific skills on the ice, such as step sequences, single and repeated jumps, as well as acceleration and deceleration of skating [55]. A key movement in skating is acceleration in a very short time and jumps resulting in sufficient flight time requiring propulsive strength and also isometric strength for stability of take-off and landing from multirotational jumps [57]. In the study by Sands et al. [47], the highest power during repeated vertical jumps explained approximately 50% of competitive rank variance in elite ice figure skaters of both sexes. These dynamic actions are underlined by coordinated muscular contractions of the lower limb during the stretch–shortening cycle (SSC) [7].

The development of lower limb muscle strength [12], explosive power [45], and sprint speed with age [40] is well known. It has previously been established that during middle childhood, strength increases relatively linearly in both girls and boys, predominantly determined by central nervous system development, resulting in improved neural mechanisms of motor unit recruitment [16]. However, during puberty, muscle strength development becomes rather nonlinear as a result of further neural and, in particular, structural and architectural changes caused mainly by increased hormonal concentration, in particular growth hormone, insulin-like growth factor, and testosterone [16, 34]. However, it has previously been established that during puberty, males exhibit a significant increase in strength and power due to a

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neuromuscular spurt, while these changes are not observed in females [34].

Successive improvements in SSC performance were also revealed with age and maturation during childhood and adolescence by cross-sectional studies [33, 46]. Changes in reactive strength index (RSI), leg stiffness, and other indicators of SSC capability have been evaluated during jumping and hopping tasks [12, 13]. The development of SSC, characterized by increased and more efficient muscle power production, can be attributed to neuromuscular and structural changes. These include the recruitment of a greater percentage of motor units during contractions and the coordination of this recruitment [20, 46]. Other factors include a more efficient feedforward mechanism [41], the development of Golgi tendon organs and muscle spindles [23], and the shortening of the electromechanical delay [41].

Assessment of changes in muscle strength capability time becomes crucial for planning a training program according to the child's biological development [10] and for injury prevention [29]. There is evidence of a relatively high incidence of ankle and knee injury in female figure skaters in the years of childhood and adolescence [28, 29]. Slater et al. [50] found that female ice skaters had restricted reach on the landing leg compared to male skaters, suggesting asymmetric hip strength and higher risk of lower extremity injury.

Knowledge of the development of lower limb muscle strength in young female ice figure skaters can be useful to assess individual changes in muscle function. Tests that include SSCs with a predominantly vertical force vector, such as triple bound, vertical, and timed tuck jumps, have been used to assess lower limb strength [51]. A combination of vertical and horizontal force components, such as repeated jumps in different directions in the hexagonal test, or with a predominantly horizontal component such as short sprint tests [31], can also be used. Furthermore, the single-legged squat itself and single-legged squat jumps were used to identify potential hip-abductor weakness in male and female ice figure skaters [57]. Several studies showed that performance and biomechanical parameters in various types of vertical jumps are significantly associated with locomotion with a predominant horizontal component of force such as a running sprint (for instance, [14, 35, 43, 48]). Furthermore, both standing broad jump and vertical jumps were strongly associated with the performance of the 1RM leg extension test in 6–12-year-old children [17]. These findings suggest some factorial overlap of various tests on lower limb muscle strength. Due to the range of kinetic and kinesiological diversity in lower limb muscle strength tests, ice skating studies are needed to explore the neuromuscular functions of particular tests that are actually assessed. Understanding the diversity in the results of the strength tests will have practical utility in reducing the potential number of tests according to the ethics of diagnosis and the time/personnel costs of testing.

The aims of the study were to investigate the age variations of the different aspects of dynamic lower limb strength in young female ice figure skaters and to reveal the latent factors that could potentially underlie performance in tests commonly used to assess lower limb muscle strength in sports. Based on the issues mentioned above, we hypothesized that there would be a factorial diversity among these tests. Exploring latent factors might contribute to understanding the specific neuromuscular aspects covered with these tests in young figure skaters. Identification of latent factors could also be useful in reducing the number of tests needed to assess lower limb power in ice figure skating practice.

Methods

Participants

Participants were young competitive female ice figure skaters ($n=438$) aged 8–13 years who were included in the Talented Youth Training Centers of the Czech Figure Skating Association (TYTC CFSA) during the years 2001–2022. The characteristics of the age groups are introduced in Table 1. The inclusion criterion was at least two years of regular training in ice figure skating. During the 3-month preseason (April–June), they participated in five training sessions a week consisting of off-ice training that included gym, track and field activity, sports games, dance, yoga, semi-specific figure skating skills, flexibility, and conditioning. During the

Table 1 Anthropometric characteristics (mean ± standard deviation) by age groups

Age	Mean age (y)	BH (cm)	BM (kg)	BMI (kg/m2)
8 years ($n=63$)	8,58 ± 0,27	129,52 ± 4,65	26,97 ± 2,8	16,04 ± 1,03
9 years ($n=76$)	9,53 ± 0,31	133,97 ± 4,9	29,66 ± 2,98	16,51 ± 1,18
10 years ($n=91$)	10,59 ± 0,28	138,49 ± 5,31	31,98 ± 3,39	16,64 ± 1,09
11 years ($n=74$)	11,52 ± 0,3	143,39 ± 6,26	34,59 ± 3,95	16,77 ± 0,94
12 years ($n=70$)	12,51 ± 0,32	147,79 ± 6,15	37,9 ± 4,53	17,3 ± 1,18
13 years ($n=63$)	13,45 ± 0,29	154,48 ± 5,71	44,14 ± 4,86	18,46 ± 1,37

SD standard deviation, *BH* body height, *BM* body mass, *BMI* body mass index

6-month competitive season (October–March), they participated in nine training units a week with seven on-ice units and two off-ice units containing nonspecific conditioning, yoga, and active recovery. Throughout the year, participants also attended 2–3 weeks of TYTC CFSA camps focused on figure skating skills and conditioning. They underwent compulsory physical testing at the beginning of the competition season, in early October during one of the camps.

The exclusion criteria were the absence of training in the last two weeks, more serious health problems 6 weeks prior to measurements, and an acute health problem at the time of measurement. The legal guardians of the participants signed an informed consent for them to participate in the TYTC CFSA, including testing. Measurements were made in accordance with the ethical standards of the Declaration of Helsinki (World Medical Association, 2013).

Procedures

The day before the testing session, participants were not subjected to any high-intensity physical activity. At the start of the testing session, anthropometric measurements were taken. The participants then performed an individual 10-min warm-up, which included a 3-min run around the gym hall, dynamic stretching of the leg muscles, and preparation exercises for jumping and running acceleration during the final part of the warm-up. In addition, participants were given time to attempt each physical test one or two times under the supervision of the researchers. The indoor sports hall testing lasted 40 min.

On the ice rink, the ice figure skaters completed a brief 10-min light warm-up and skating session, which included basic exercises for dynamic balance and push-offs from the skate edges. Following this, they participated in an on-ice sprint test with all tests in the ice rink hall lasting around 15 min.

Anthropometric measurements

Stature was measured standing without shoes using a wall-mounted measuring band with an accuracy of 1 cm. Body mass was measured using a TANITA BC 545 scale (Tanita, Japan) with an accuracy of 0.5 kg.

Tests of lower limb dynamic strength

Participants underwent the standardized lower limb dynamic strength tests in the order listed below. The tests included jumping characterized by a predominant horizontal or vertical component of forces, and maximal short distance running and skating. A 5-min rest preceded each test.

Standing long jump (SLJ) test

The SLJ was performed according to the EUROFIT ® standardized physical fitness test battery manual [9]. From a slight crouch position, with feet approximately shoulder-width apart and parallel, the participant squats, leans forward, bumps, and bounces down with the simultaneous swing of their arms forward and jumps as far as possible. The distance of the longest jump of the two trials was used, with an accuracy of 1 cm. The rest interval between the two trials was 2 min. Before the test trials, the participant performed one practice trial. The SLJ is a test used to assess explosive leg power or the ability to apply force in a horizontal direction [36]. The SLJ used in 6–12 year-old children was reported to be highly reliable, with a 95% CI for test–retest ICC 0.93–0.95 [17].

Triple jump test with right/left leg (TJR/TJL test)

This test evaluates an individual's ability to decelerate in contact with the ground for optimal landing and to rapidly transition from eccentric to concentric muscle contractions, i.e., reactive strength [49]. The participant from a standing position, on one leg behind the start line, performed three maximal consecutive hops for distance without pausing between hops and landing from the last hop on 2 feet. The participant performed three trials for each leg, with a 2-min rest interval after each trial. Before the test trials, one practice trial was executed for each leg. The distance from the rebound line to the nearest mark of impact of the foot sole after the third rebound was measured with an accuracy of 1 cm. The longest of three attempts on each leg was recorded. The triple jump test showed excellent test–retest reliability with an ICC of 0.94 to 0.95 [11], and another previous study confirms these results with ICC values ranging from 0.76 to 0.92 [39].

Repeated vertical jump (RVJ) test

The RVJ test consisted of repeated vertical jumps for 10 s on the FITRO Jumper (FiTRONiC, s.r.o. Bratislava, Slovakia). Each participant, wearing trainers, stood on a jump ergometer with their arms fixed on their sides and held a rubber Thera-band. The rubber band looped around their waist and their arms prevented the accompanying arm movement during the jump. The task was to maximize jump height and minimize ground contact time (Tc). The participants performed three trials of repeated vertical jumps with a 30 s rest between the trials. Before the measured trials, the participant performed one practice trial approximately 5 s long. The height of each jump (h; cm) was derived from flight time (ft; s) using the formula: $h = (g \times ft2) / 8$. The power in the concentric phase of take-off (Pact, W/kg) was calculated using the formula Pact = (g2.ft)*(Tc + ft)/4Tc, where g is the gravitational constant 9.81 m/s2. The RSI was calculated using the equation: RSI = h/Tc [18]. In each trial, the highest Pact achieved in three jumps was averaged. From the trial with the highest average Pact, the average of Tc, h, and RSI of the three jumps were used for the subsequent analysis. The FITRO jumper measures Tc and ft with an accuracy of 1 ms [52] and RSI with reliability ICC = 0.924 [59].

15-m running acceleration test

A band was placed around the waist of the participant, with a guide wire connected to the FiTRO speed check device (FiTRONiC, Bratislava, Slovakia) and attached to the participant. *Participants were asked to run from their standing position at their own discretion, with a maximum effort, for a distance of 20 m. They were instructed to start slowing down the run until the wire was detached.* Before the measured trial, the participant performed one practice trial. In case of technical, organizational, or task execution problems, the running acceleration trial was repeated. The total running acceleration time (Rt15m, s) and the average velocity were measured for an interval of 0.00 s–1.00 s of running acceleration (Rv1.s). The 20-m sprint test showed an excellent test–retest reliability of r = 0.90 in children aged 7–11 years [2]. A systematic review in rugby shows that both the 10 and 20 m sprint tests have good test–retest reliability, ICC = (10 m) 0.87 and (20 m) 0.92 [6].

15-m skating acceleration test

The participants were in a starting position with the back leg's skate blade on its inner edge and the front leg's skate blade on the toe pick. A band around the waist of the participants with a guide wire connected to the FiTRO speed check device (FiTRONiC, Bratislava, Slovakia) and attached to the participants. Subsequently, they were asked to skate in a straight line with a maximum effort of 20 m. Each participant conducted one trial. Before the measured trial, the participant performed one practice trial. In case of technical, organizational, or task execution problems, the ice skating acceleration trial was repeated. The total time achieved (St15m) and the average velocity at an interval of 0.00–1.00 s (Sv1s) were recorded. The test–retest reliability for the total 20 m skating time and the mean speed at the 1st second of skating was found to be 0.989 and 0.968, respectively [26]. To our knowledge, no other studies have reported the test–retest reliability of 20 m skating time in this population.

Data analysis

In the first step, outliers of the test scores in the sample n = 472 were identified as any observation outside the range (Tukey´s fences): [Q1–1.5(Q3–Q1), Q3 + 1.5(Q3–Q1)] [53], where Q1 and Q3 are the lower and upper quartiles. After excluding cases with one or more test scores being outliers, the data of the sample $n = 438$ were normally distributed when tested with the Shapiro–Wilk and Kolmogorov–Smirnov test. The mean and standard deviation were used as descriptive statistics to characterize the results of leg strength tests in particular age groups.

One-way multivariate analysis of variance (one-way MANOVA) was used to identify differences in leg strength test scores based on age. To identify the significance of age for the particular leg strength variables, univariate ANOVA and the post hoc Tukey test for pairwise comparisons between ages were used. The 11 leg strength variables were subjected to principal component analysis (PCA) to reveal the significant latent factors of these variables. This procedure was followed by varimax rotation to increase information on factor loadings and to reduce the number of leg strength variables (tests) without loss of information. In other words, the varimax rotation was performed on the initial solution by PCA. The PCA and varimax rotation procedures were performed on data from all age groups, particularly for the youngest group (8 + 9 years, group 8–9) and the oldest group (12 + 13 years, group 12–13). The level of significance was set at 0.05 for all statistical tests. Data analyses were performed using IBM SPSS Statistics, 28.0 (IBM, Armonk, NJ, USA).

Results

Figure 1 suggested changes in all test variables with age, except Tc, which remained stable across the ages of 8–13 years. At the general level, differences between age groups were indicated in terms of the variables of the leg strength tests, using Wilks' Lambda and MANOVA results (Table 2). The ANOVA showed a significant effect of age for all test variables, except contact time (Tc) in the RVJ test.

According to the results of univariate ANOVA, age was a significant factor for the performance of the SLJ test, the triple jump test for both legs, the jump height in the RVJ test, and the time in the skate sprint test (Table 3).

Performance in the SLJ test showed a statistically significant improvement year by year among young figure skaters ($p \leq 0.002$), except for no significant differences between ages 8 and 9 and between ages 11 and 12 years. Performance in the triple jump test executed on the left and right legs improved consistently across all ages ($p < 0.001$).

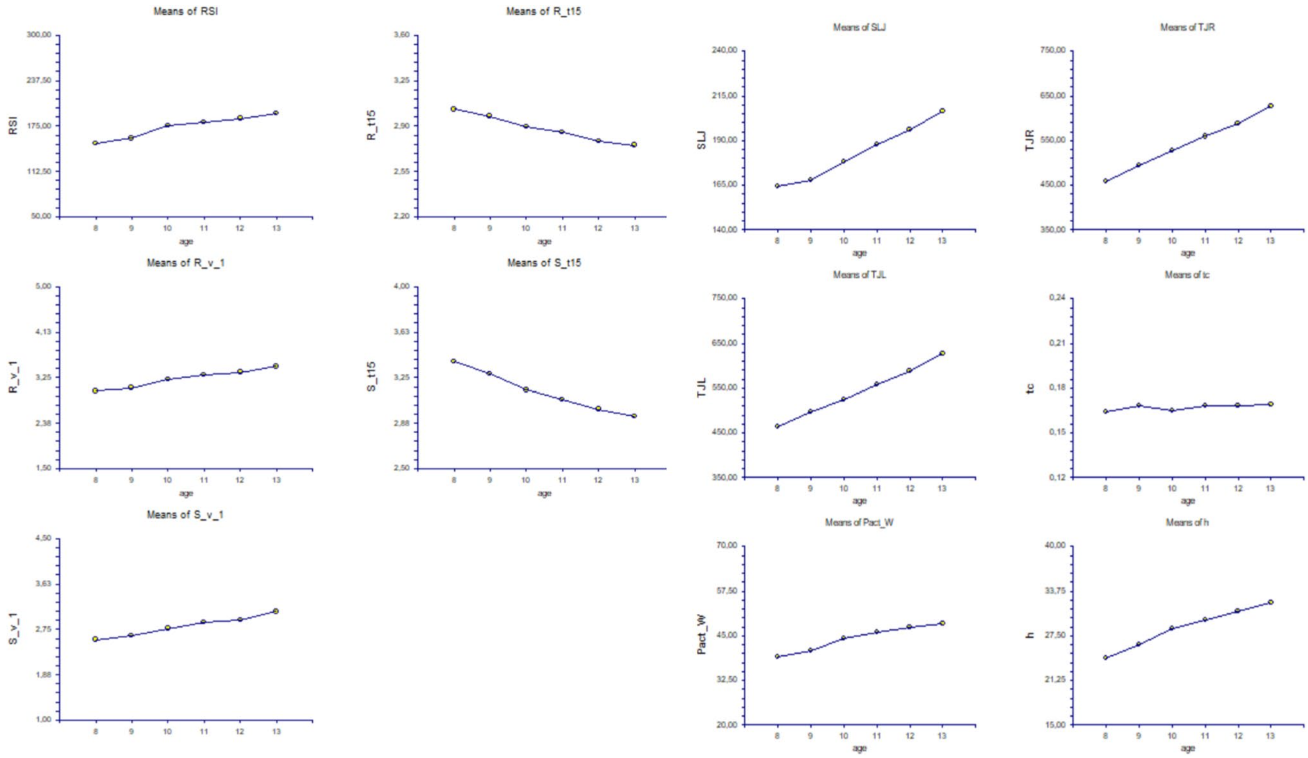

Fig. 1 The test variables for female figure skaters by age. Note: RSI (cm/s)—reactive strength index; R_t15 (s)—total time in the 15-m running acceleration test; SLJ (cm)—distance covered in the standing long jump test; TJR, TJL (cm)—distance covered in the triple jump test with the right and left legs, respectively; R_v_1 (m/s)—average velocity for an interval of 0.00 s–1.00 s of running acceleration; S_t15 (s)—total time in the 15-m skating acceleration; tc (s)—contact time in the repeated vertical jump test; S_v_1 (m/s)—average velocity for an interval of 0.00 s–1.00 s of skating acceleration; Pact (W/kg)—highest average mechanical power during a concentric phase in the repeated vertical jump test; h (cm)—highest average jump height in the repeated vertical *jump test*

Table 2 The results of MANOVA

		Test value	*DF1*	*DF2*	*F ratio*	*p*
	Wilks' lambda	0.261	55	1952	11.94	< 0.001
	Hotelling–Lawley trace	2.489	55	2097	18.98	< 0.001
	Pillai's trace	0.831	55	2125	7.70	< 0.001
	Roy's largest root	2.354	11	425	90.93	< 0.001
SLJ	SLJ	17,863.165	5	431	109.84	< 0.001
Triple jump test	TJR	250,635.476	5	431	147.81	< 0.001
	TJL	233,439.795	5	431	117.91	< 0.001
Repeated vertical	Tc	0.000	5	431	0.98	0.432
jump test	Pact	929.318	5	431	22.10	< 0.001
	H	562.527	5	431	53.06	< 0.001
	RSI	17,189.137	5	431	18.20	< 0.001
Running sprint test	Rt15m	0.771	5	431	28.81	< 0.001
	Rv1s	2.170	5	431	12.30	< 0.001
Skate sprint test	St15m	1.978	5	431	43.42	< 0.001
	Sv1s	2.723	5	431	12.53	< 0.001

SLJ (cm)—standing long jump, TJR (cm)/TJL (cm)—triple jump test with right/left leg, Tc (s)—contact time, Pact (W/kg)—power in the active phase of the take-off, h (cm)—height of the jump, RSI—reactive strength index, Rt15m (s)—running 15 m, Rv1s (m/s)—running velocity in 1st s, St15m (s)—skating 15 m, Sv1s (m/s)—skating velocity in 1st s. DF1; DF2—degrees of freedom, F ratio—F-test statistics, p—significance value, DF1, 2—degrees of freedom, p—a level of probability

Table 3 Results of univariate ANOVA—statistical significance of age for particular variables of the lower limb strength tests (p values)

SLJ	< 0.001	**Tc**	0.788	**Rt15m**	0.378
TJR	< 0.001	**Pact**	0.312	**Rv1s**	0.374
TJL	< 0.001	**H**	0.049	**St15m**	0.030
		RSI	0.111	**Sv1s**	0.812

SLJ (cm)—standing long jump, TJR (cm)/TJL (cm)—triple jump test with right/left leg, Tc (s)—contact time, Pact (W/kg)—power in the active phase of the take-off, h (cm)—height of the jump, RSI—reactive strength index, Rt15m (s)—running 15 m, Rv1s (m/s)—running velocity in 1st s, St15m (s)—skating 15 m, Sv1s (m/s)—skating velocity in 1st s

The jump height in the RVJ test was higher in 10–13 years old compared to 8 years old ($p = 0.046$, 0.001, 0.009, 0.001), and 13 years old also showed higher values compared to 9 years old ($p = 0.0040$). Additionally, 12 and 13 years old achieved higher RSI compared to 8 and 9 years old ($p = 0.021$, 0.022, and 0.031, 0.030, respectively). However, the power in the concentric phase of take-off (Pact) was significantly higher in 13 years old than in 8 years old only ($p = 0.034$).

The variables Rt15m and Rv1s of the 15-m running acceleration test did not change significantly across the ages, with the exception of the shorter running time of 13 years old compared to 8 years old ($p = 0.044$). 13-Year-old figure skaters demonstrated shorter time in the 15-m skating acceleration test compared to 8–11 years old ($p = 0.048$, 0.007, 0.029, 0.026).

The results of the PCA and varimax rotation on data of all age groups showed that a set of 11 leg strength variables covered three significant non-correlated latent variables. The leg strength variables with the highest significant factor loadings on the first factor which described the largest variance were jump height, Pact, and RSI of the RVJ test. There was a significant negative loading of Tc by factor 1 (Table 4). The second significant factor (factor 2) had high factor loadings for all variables measured in both the running and skating acceleration tests (Table 4). Factor 3 had significant loadings for all variables in the three jump tests, except Tc (Table 4).

The results of varimax rotation used on the initial solution of PCA for data for the age group 8–9, group 10–11, and group 12–13 years showed significant loadings by particular factors on identical test variables (Table 5, 6, 7).

Discussion

One of the aims of this study was to investigate the age variations of the different aspects of dynamic lower limb strength in young female figure skaters. The data showed gradual improvement with age in all observed parameters except for Tc during the RVJ test. Because in all performed movement tasks, force in the vertical or the horizontal direction was produced during the SSC (either fast or slow), this result supports the evidence that SSC capability naturally improves during growth and maturation (Lloyd et al., 2012; [46]). The observed positive age effect on performance in the tests used in the current study is in line with findings of most previous studies on youth which point to improvement in

Table 4 Factor loadings of leg strength variables after varimax rotation for all age groups

Test	Variable	Factor 1	Factor 2	Factor 3
SLJ test	SLJ	0.029	0.253	**0.864**
Triple jump test	TJR	0.136	0.264	**0.908**
	TJL	0.124	0.260	**0.902**
Repeated vertical jump test	Tc	**0.913**	0.030	0.162
	Pact	**0.803**	0.112	**0.527**
	h	**0.482**	0.173	**0.755**
	RSI	**0.866**	0.104	**0.468**
Running sprint test	Rt15m	0.032	**0.780**	0.324
	Rv1s	0.012	**0.797**	0.143
Skate sprint test	St15m	0.081	**0.854**	0.292
	Sv1s	0.058	**0.829**	0.079

SLJ (cm)—standing long jump, TJR (cm)/TJL (cm)—triple jump test with right/left leg, Tc (s)—contact time, Pact (W/kg)—power in the active phase of the take-off, h (cm)—height of the jump, RSI—reactive strength index, Rt15m (s)—running 15 m, Rv1s (m/s)—running velocity in 1st s, St15m (s)—skating 15 m, Sv1s (m/s)—skating velocity in 1st s

Table 5 Factor loadings of leg strength variables after varimax rotation in the age group of 8–9 years

Test	Variable	Factor 1	Factor 2	Factor 3
SLJ test	SLJ	0.121	0.086	**0.715**
Triple jump test	TJR	0.100	0.165	**0.897**
	TJL	0.137	0.156	**0.898**
Repeated vertical jump test	Tc	**0.862**	0.093	0.171
	Pact	**0.903**	0.044	0.361
	h	**0.637**	0.056	**0.573**
	RSI	**0.946**	0.089	0.283
Running sprint test	Rt15m	0.023	**0.793**	0.222
	Rv1s	0.052	**0.765**	0.082
Skate sprint test	St15m	0.183	**0.838**	0.165
	Sv1s	0.106	**0.767**	0.016

SLJ (cm)—standing long jump, TJR (cm)/TJL (cm)—triple jump test with right/left leg, Tc (s)—contact time, Pact (W/kg)—power in the active phase of the take-off, h (cm)—height of the jump, RSI—reactive strength index, Rt15m (s)—running 15 m, Rv1s (m/s)—running velocity in 1st s, St15m (s)—skating 15 m, Sv1s (m/s)—skating velocity in 1st s

Table 6 Factor loadings of leg strength variables after varimax rotation in the age group of 10–11 years

Test	Variable	Factor 1	Factor 2	Factor 3
SLJ test	SLJ	0.012	0.342	**0.880**
Triple jump test	TJR	0.130	0.310	**0.893**
	TJL	0.143	0.264	**0.907**
Repeated vertical	Tc	**0.893**	0.011	0.200
jump test	Pact	**0.847**	0.201	**0.671**
	h	**0.591**	0.134	**0.701**
	RSI	**0.876**	0.185	**0.586**
Running sprint test	Rt15m	0.061	**0.767**	0.408
	Rv1s	0.030	**0.698**	0.251
Skate sprint test	St15m	0.042	**0.839**	0.321
	Sv1s	0.087	**0.861**	0.011

SLJ (cm)—standing long jump, TJR (cm)/TJL (cm)—triple jump test with right/left leg, Tc (s)—contact time, Pact (W/kg)—power in the active phase of the take-off, h (cm)—height of the jump, RSI—reactive strength index, Rt15m (s)—running 15 m, Rv1s (m/s)—running velocity in 1st s, St15m (s)—skating 15 m, Sv1s (m/s)—skating velocity in 1st s

Table 7 Factor loadings of leg strength variables after varimax rotation in the age group of 12–13 years

Test	Variable	Factor 1	Factor 2	Factor 3
SLJ test	SLJ	0.052	0.052	**0.883**
Triple jump test	TJR	0.182	0.081	**0.917**
	TJL	0.086	0.092	**0.919**
Repeated vertical	Tc	**0.815**	0.019	0.200
jump test	Pact	**0.953**	0.044	0.203
	h	**0.702**	0.037	**0.461**
	RSI	**0.975**	0.039	0.190
Running sprint test	Rt15m	0.047	**0.743**	0.135
	Rv1s	0.030	**0.797**	0.007
Skate sprint test	St15m	0.073	**0.869**	0.032
	Sv1s	0.024	**0.815**	0.049

SLJ (cm)—standing long jump, TJR (cm)/TJL (cm)—triple jump test with right/left leg, Tc (s)—contact time, Pact (W/kg)—power in the active phase of the take-off, h (cm)—height of the jump, RSI—reactive strength index, Rt15m (s)—running 15 m, Rv1s (m/s)—running velocity in 1st s, St15m (s)—skating 15 m, Sv1s (m/s)—skating velocity in 1st s

reactive strength [13], explosive strength [15], and running speed ([5], Malina et al., 2003; [37]) with age. Nevertheless, although the data of univariate ANOVA showed that age was a significant factor for performance of the SLJ test, the triple jump test for both legs, the jump height in the RVJ test, and the time in the skate sprint test, comparisons between consecutive age groups confirmed consistent improvement across all ages only in the case of the triple jump test for both legs. We believe that this improvement between consecutive age groups, which was not observed in other tests, can primarily be explained by increments in body height, which could be an important factor for horizontal jump performance rather than for vertical jump performance [58]. This assumption is also indirectly supported by the results of the SLJ test, i.e., the other test with horizontal force production during the SSC, where year by year improvements were also observed, except for ages 8 and 9, and 11 and 12 years.

It should be noted that given that the tested figure skaters have been participating in the training process for a long time, it can be assumed that the mentioned changes were caused by both natural-occurring adaptations and training and competition workload. However, we are unable to determine the degree of influence of natural development and the influence of training load. In addition, it can be assumed that their effect on the observed figure skaters was different in individual age groups due to the periods of accelerated adaptation which occur at the age of 8–13 for the assessed fitness components [19]. No significant changes in Tc during the RVJ test in consecutive age groups in our study are in line with the previous studies on youth (see, e.g., [34, 44]). The absence of significant improvement in consecutive years, especially at the age of 9–12, in parameters of the RVJ test and both sprinting tests is consistent with most previous studies focused on youth female figure skaters [33], other sports (for instance, Emonds et al., 2017), but also the non-sports population of girls (for instance, Faigenbaum, 2019; [32]).). In the case of the sprint tests included into physical testing, age was confirmed as a significant factor only in the case of the 15-m skating acceleration test, which together with the results of post hoc tests indicate that the skating test is more sensitive to changes due to specific skating training.

The values of the monitored physical fitness characteristics and their changes in the most successful figure skaters in individual age groups presented in this study could be used in sport practice to identify talent and increase the effectiveness of long-term performance development in female figure skating by youth with respect to the specific needs of individuals.

Factor 1 was found to significantly underlie mechanical power during the concentric phase of repeated vertical jumps (Pact), jump height, ground contact time (Tc), and RSI, all measured with the RVJ test. Intercorrelations among these four variables were suggested. First, according to the mechanical model of vertical jump, the height of jumping is directly determined by the vertical take-off velocity of the center of mass (COM), which is given by the mechanical power applied to the COM during the concentric phase of SSC [1]. Second, the RSI is related to jump height and thus indirectly to mechanical power during the concentric phase, as it is calculated by jump height divided by Tc during the eccentric and concentric phases of the SSC [18]. The RSI has been described as the capability of the low extremity muscles to change quickly from an eccentric to concentric contraction involved in SSC [18]. SSC may be attributed to the muscle–tendon complex, including the recruitment of a higher percentage of motor units during contractions, coordination of this recruitment [20], a more efficient feedforward mechanism [41], the development of Golgi tendon organs and muscle spindles [23], and the shortening of the electromechanical delay of muscles [41]. The faster change from eccentric to concentric contraction of the leg muscles involved in SSC reflects a shorter Tc. In contrast, a prolonged eccentric amortization phase during landing can lead to impaired use of elastic energy for subsequent take-off [24, 56], excluding stretch reflex initiation [22], and a decrease in neural excitation for the concentric phase of SSC [8]. Our sample of figure skaters jumped with a mean Tc = 167 ± 18 ms across all ages, with high homogeneity (CV = 10.8%). Based on ground contact thresholds, Tc < 250 ms has been classified as fast SSC activity [46]. The results of the study suggested that the Factor 1 could be interpreted as the fast SSC capability of leg muscles for bilateral force in the vertical direction. Due to all of these proposed mechanisms, factor 1 can represent the fast SSC capability for jumping in the vertical direction.

In our study, the explored latent Factor 2 significantly underlies the time and speed variables measured in the short (15-m) forward linear running and on-ice skating acceleration tests. A common characteristic of these tests is acceleration of the body mass, from predominantly horizontal forces produced by the legs during repeated unilateral plyometric muscle actions. From a mechanical point of view, the horizontal component of the resultant ground reaction force (GRF) is the key mechanical feature of running acceleration performance, regardless of skill level [38]. Similarly, for ice skating sprint performance, the study by [42] with female ice hockey players showed that the capacity to generate high amounts of horizontal power and force during the first steps on the ice is paramount for forward skating acceleration performance. These authors also found the largest associations between running and skating sprints at a distance of 5–30 m. Similarly, in the study by Krause et al. [30], the off-ice sprint time was more predictive of the on-ice skating performance, accounting for 65.4% of the variability in forward skate time.

However, there are some kinematic and kinesiological differences between running and skating sprints. In running sprints, athletes drive more force into the ground for shorter time instances to take advantage of elasticity, so that the athlete is vaulted further and faster forward on each stride. In skating sprints, ice hockey players modify their stride mechanics to push laterally to essentially move to a larger 'gear' to create higher velocities of movement [25]. We suppose that short linear skating of figure skaters could be performed with a similar mechanics. This multi-joint dynamic action specificity of skating sprint corresponds to the findings of significant symptoms of high-level skating, such as greater hip abduction during ice contact to push-off [4], greater hip flexion, knee extension, plantar flexion, and greater rates of posterior tilt of the pelvis, thigh, and shank at propulsion [54]. Furthermore, while the stride frequency remains relatively constant in running sprints over several seconds, the stride frequency of skaters slows down to accommodate a modified and more efficient stride mechanics [25]. In spite of some kinesiological specificities of running and one-ice sprinting, both modes of maximal very short locomotion include a very similar pattern of forces developer during muscle actions. Thus, Factor 2 could be interpreted as a neuromuscular sprinting ability, including a fast SSC capability for repeated unilateral force development in the horizontal direction. The results of our study indicate that the assessment of the horizontal component of the lower limb strength is sufficient to use as the only ice skating acceleration test, as it is more specific for ice figure skaters.

The obtained Factor 3 showed the highest factor loading for both jumps with predominant horizontal forces included in the SLJ test, and TJR/TJL tests. During these horizontal jump tests, a slow SSC capability is manifested by efficient muscle power production associated with quick absorption upon landing during the eccentric phase of the SSC before transferring to the concentric phase of the jump and also horizontal force production during the subsequent concentric phase of the SSC [18].). Compared to fast SSC in vertical jumping, slow SSC is typical of an increased contraction time and working range, enabling greater force production (Cormie et al., 2011 [18],). From an electromyographic perspective, there is a lower activation level of the biarticular rectus femoris and hamstrings during horizontally directed jumps, which is probably the cause of lower knee extension moment for horizontal jump [21].). It means that the activity of muscles adopts to the jump direction.

Based on the notes above, Factor 3 could be interpreted as a jumping ability with a slow SSC capability for the development of force in the horizontal direction. In addition to horizontal jumps, Factor 3 was also significantly included in jump height, mechanical power during take-off (Pact), and RSI during repeated vertical jumps that were strongly related to Factor 1. As the factors were investigated as uncorrelated (orthogonal), vertical jumping performance was contributed not only by the fast SSC capability of the legs (Factor 1), but also by another neuromuscular component that would be common for jumping, regardless of whether there was a predominant vertical or horizontal component of forces. Therefore, the specific functional entity common for jumping should be a specific neuromuscular pattern of take-off and/or landing that is different from the pattern of take-off and landing during ice skating and running acceleration.

The pattern of factor loadings of test performance parameters was very similar across the age range of 8–13 years.

This is obvious when comparing the factor loadings of the test variables found after varimax rotation in the age group of 8–9 years and 12–13 years (see Tables 4 and 5). These results suggest that the tests used can provide information on the same neuromuscular qualities of female figure skaters across the age range of 8–13 years, providing factor validity. The reason for these findings could be that there are no large changes in the neuromotor pattern for the movements involved in the tests. Feedforward motor control and rapid online motor corrections improve during middle childhood and stabilize around the age of 10–13 years [3, 27], related to neural maturation, such as myelination, the growth of white matter networks, and synaptogenesis (Ruddock et al., 2015).). In trained individuals, internal models of motor skills can be developed earlier. The five tests investigated in the recent study can be used to assess the muscle strength of lower limb associated with jumping and skating actions in young female ice figure skaters.

The study was based on data from a large sample. However, the main limitation of the study is that it was a cross-sectional study. To increase the validity of findings regarding developmental changes in various functional aspects of lower limb muscle strength in young ice figure skaters, a longitudinal study would be needed in future research be necessary in future research.

In summary, changes in particular indicators of lower limb muscle strength between 8 and 13 years of age in elite female ice figure skaters exhibited gradual improvement with age in all parameters observed except for Tc during the RVJ test. However, only performance in tests that emphasize the horizontal component of force showed significant improvements year-over-year. The set of tests used in this study can provide an assessment of three neuromuscular qualities derived from the revealed factors: the fast SSC capability to jump in the vertical direction, the slow SSC capability to jump in the predominant horizontal direction, and the fast SSC capability to skate and run. However, some tests and parameters have been shown to be related to the same factor. The following way saves time and personal costs: (i) for the assessment of the fast SSC capability to jump in the vertical direction, the repeated vertical jump test would be useful, using a dynamometric device or any tool that provides jump height data; (ii) to assess the slow SSC capability to jump in the horizontal direction, it would be sufficient to use the triple jump test on one selected leg; (iii) for the assessment of the fast SSC capability during skating, the 15-m skating acceleration test with a measurement of time is sufficient.

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Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval This study does not involve human participants, sensitive personal data, or any procedures that require ethical approval according to Czech Act No. 372/2011 Coll., on Health Services or related legislation. Therefore, approval from the ethics committee is not applicable.

Informed consent For this type of study, formal consent is not required.

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