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Description

Trends in pairs figure skating have shown that increasingly difficult jumps have become an essential aspect of high-level performance, especially in the latter part of a competitive program. We compared a repeated jump power index in a 60 s repeated jump test to determine the relationship of repeated jump test to competitive rank and to measure 2D hip, knee, and ankle angles and angular velocities at 0, 20, 40, and 60 s. Eighteen National Team Pairs Figure Skaters performed a 60 s repeated jump test on a large switch-mat with timing of flight and ground durations and digital video recording. Each 60-s period was divided into 6, 10-s intervals, with power indexes (W/kg) calculated for each 10-s interval. Power index by 10-s interval repeated measures ANOVAs (RMANOVA) showed that males exceeded females at all intervals, and the highest power index interval was during 10 to 20 s for both sexes. RMANOVAs of angles and angular velocities showed main effects for time only. Power index and jumping techniques among figure skaters showed rapid and steady declines over the test duration. Power index can predict approximately 50% of competitive rank variance, and sex differences in jumping technique were rare.

Keywords

fatigue, jumping, anaerobic, figure skating, force

Disciplines

Sports Sciences

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Research article

A comparison of pairs figure skaters in repeated jumps

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Abstract

Trends in pairs figure skating have shown that increasingly difficult jumps have become an essential aspect of high-level performance, especially in the latter part of a competitive program. We compared a repeated jump power index in a 60 s repeated jump test to determine the relationship of repeated jump test to competitive rank and to measure 2D hip, knee, and ankle angles and angular velocities at 0, 20, 40, and 60 s. Eighteen National Team Pairs Figure Skaters performed a 60 s repeated jump test on a large switch-mat with timing of flight and ground durations and digital video recording. Each 60-s period was divided into 6, 10-s intervals, with power indexes (W/kg) calculated for each 10-s interval. Power index by 10-s interval repeated measures ANOVAs (RMANOVA) showed that males exceeded females at all intervals, and the highest power index interval was during 10 to 20 s for both sexes. RMANOVAs of angles and angular velocities showed main effects for time only. Power index and jumping techniques among figure skaters showed rapid and steady declines over the test duration. Power index can predict approximately 50% of competitive rank variance, and sex differences in jumping technique were rare.

Key words: Anaerobic, fatigue, figure skating, force, jumping.

Introduction

Competitive pairs figure skating consists of performances of both "short" and "long" programs, which are several minutes in duration, and require intricate skating skills, dance, acrobatics, pirouettes, and spinning or non-spinning jumps. In recent years, and like other sports (Sands, 2000; Sands et al., 2001a; 2001b), the increased emphasis on jumping skills has become apparent, with athletes exhibiting a relentless quest for performing more and higher jumps, with an increased number of spins being executed during the jumps. Moreover, the modern pairs figure skaters have seen an escalation of partner throws where the male partner generally throws the female partner high in the air to accomplish multiple spins prior to landing. In addition, there has been an increased emphasis to perform difficult skills at or near the end of the program to attain a "balanced" distribution of difficult skills (Kestnbaum, 2003). Of course, the demand for more jumping skills has resulted in an increased demand for lower extremity strength, power, and "power endurance" to achieve high-difficulty skills while fatigued (Sands, 2000; Sands et al. 2001a; 2001b; 2003).

The stretch-shortening cycle is the primary mechanism of skilled jumping, particularly in high-speed jumping sports. Stretch-shortening cycle fatigue has been implicated as a potential contributor to stress fractures via less joint flexion in some joints while greater range of motion in others. Stretch-shortening cycle fatigue also tends to elicit greater ground-reaction forces, and less neuromuscular activation for a given impact (James et al., 2006). Stretch-shortening cycle fatigue has been shown to last for days after maximal fatiguing stretch-shortening cycle efforts (Avela and Komi, 1998; Avela et al., 1999). The repeated jumps test was created to test long-term stretch-shortening cycle performance and the accompanying fatigue as an athlete performance characteristic (Bosco et al., 1983; Bosco et al., 1982; Viitasalo and Bosco, 1982). The repeated jump test seems to be a relevant and logically valid test of performance for pairs figure skaters because of the duration of skating performance programs and the stretch-shortening cycle (Sands et al., 2004).

The main purpose of this study was to compare the performances on the repeated jump test (Bosco, Komi, et al., 1983) with U.S. National Team Pairs Figure Skaters to determine potential differences by sex, repeated jump test fitness, and joint angular kinematics. A secondary purpose was to examine the relationship between test performance and the figure skaters national team rank.

Methods

Subjects

Thirty-six U.S. Figure Skating National Team pairs volunteered for this study ([*M* ± *SD*] males n = 18, height 1.79 ± 0.08 m, mass 77.5 ± 7.0 kg, age 22.7 ± 2.7 yr, training age 11.5 ± 3.1 yr; females n = 18, height 1.56 ± 0.05 m, mass 47.5 ± 6.3 kg, age 18.3 ± 3.4 yr, training age 10.1 ± 3.3 yr). The sample included 12 senior national pairs and six junior national pairs. The kinematic analyses were limited to 15 competitive pairs (30 athletes) due to digital video file conversion problems. The subjects provided informed consent for the study via the U.S. Olympic Committee's human subjects' protocols and USA Figure Skating human subjects' protocols. The study was approved by the sponsoring university's Institutional Review Board on the Study of Human Subjects for archived data.

Equipment and instrumentation

The repeated jump test was performed on a large, switch-mat (Newtest OY, Oulu, Finland) interfaced to a personal computer via custom software as described in several

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previous experiments of repeated jump tests (Sands, 2000; Sands et al., 2001a; 2001b; 2004). The software recorded time to the microsecond, and time-intervals were obtained by the opening and closing of the switch-mat circuit via take-offs and landings. The test was computer controlled.

Kinematic data were acquired with a standard digital video camera (60 Hz, Panasonic Corporation of North America, Secaucus, NJ, USA). Two-dimensional calibration was performed using a rectangular calibration frame (1.00 x 1.10 m). Circular reflective markers were placed at anatomical locations indicative of joint centers of the hip (greater trochanter), knee (joint line), and ankle (lateral malleolus). The torso point was placed at the level of the xiphoid process and on the 12th rib at the inferior-lateral angle. A toe marker was placed on the lateral side of the 5th metatarsal head. Internal angles were defined as hip (torso, hip, knee), knee (hip, knee, ankle), and ankle (knee, mallelolus, and toe). Kinematic data were analyzed using Peak Performance Technologies system (Peak Performance Technologies, Motus Version 9.0, Centennial, CO).

Procedures

Power index: Data were collected at the U.S. Olympic Training Center Athlete Performance Laboratory in conjunction with a USA Figure Skating National Team training camp. Athletes were tested in a station format, rotating through a variety of physical tests and other information-gathering stations. As the athletes came to the repeated jump test station, they performed a self-selected warm-up and were informed about the test protocol. The test began with the athlete standing upright on the switch-mat, with the hands resting on the hips. The hands were required to remain on the hips throughout all the jumps and landings. The athlete was placed in a 90° knee flexion position via a handheld goniometer to familiarize him or her with the depth of knee flexion required during the transition from a landing to the succeeding maximum vertical jump. On a countdown the athlete began the test by performing rapid maximal vertical jumps and landings. Knee flexion was observed by the investigator. Feedback on any jump where the athlete failed to achieve or exceeded the 90° criterion was noted verbally, and the athlete was told whether he or she was too high or too low. Maximum vertical jumps and landings continued for one minute, at which time the test was completed.

Kinematics: Kinematic data were collected via standard digital video cassettes of the entire 60 s of jumping. Data were captured from the digital video tapes and stored on a computer using the Peak Performance Technologies software system. Three consecutive jumps were manually digitized at 0 s from the first moment of flight up to the peak height of the third jump. At 20 s, the 2nd of three jumps occurring at 20 s with jump one and jump three occurring before and after the jump at 20 s were digitized for analysis. The same approach as the 20 s three jumps was used at 40 s. At 60 s the final three jumps prior to the end of the test were analyzed beginning with the instant of the takeoff of the first flight phase to the peak height of the last jump that occurred at approximately 60 s. Three angles were determined: hip (torso center, hip, knee), knee (hip, knee, ankle), and ankle (knee, ankle, toe). Relative angular position, displacement, and velocity of the three angles were determined from the kinematic data.

Analyses

Ground contact and flight times were recorded via the switch-mat's computer interface and stored in computer files. An average power index was calculated based on the work of Bosco (1983). Bosco and colleagues calculated a power value based on flight time that was later challenged by Hatze (1998) and shown to be inaccurate. The current investigators have referred to the units of average power for the repeated jump test as W/kg, but have recognized that these units are an estimate and therefore have designated these values a 'power index.' Regression analyses were calculated to determine the linear trends of both ground-times and flight-times, along with ground-time and flight-time Y Axis Intercepts. Further data processing included dividing the 60-s test period into six, 10-s time-intervals for the analysis of the overall trends of the average power index, flight-times, and ground-times for each interval. A 2x6 (sex x 10 s time-intervals) repeated measures ANOVA was calculated on the average power indexes. A backward method multiple regression procedure was used to model the following variables with figure skaters pairs rank: repeated jump test fatigue index (percentage change in power index from the first 10 s to the last 10 s), training age, height, mass, and average power-index (W/kg). Pearson product-moment, zero-order, correlation coefficients were calculated between individuals within the intact male and female pairs, and between pair ranks and measured variables.

Kinematic analyses of the three jumps involved analyses of the ascent of the first jump, descent of the first jump, ascent of the second jump, descent of the second jump, and ascent of the third jump. This approach involved the analysis of three ascents and two descents. The three jumps and their phases (i.e. ascents or descents) were analyzed as trials data for trials reliability information, and the trend free trials were then averaged, and the averages were used for further data analyses (Henry, 1950; Henry, 1967; Kroll, 1967). The three jumps at each kinematic time-interval were averaged for a final value representative of the athlete's efforts at 0 s, 20 s, 40 s, and 60 s. Twelve, 2x4 (sex x kinematic time-interval) repeated measures ANOVAs (RMANOVAs) were calculated on the three joints (hip, knee, ankle) and ascent or descent positions and joint peak velocities. Type I error protection was achieved via the Dunn-Sidak method (Sokal and Rohlf, 1969) resulting in an alpha level of 0.001.

Results

The power-indexes for each 10 s of the repeated jump test, by sex and 10 s time-intervals, are shown in Figure 1. The RMANOVA showed statistical main effects for sex and time, but a non-statistically significant interaction (sex x time). The between-subjects effects (sex) showed a partial η^2 of 0.503, confidence interval 2.806 to 5.783 power index. The within-subjects effect (10 s time-intervals) showed a partial η^2 of 0.76. The 95% confidence intervals for males and females power index by 10s

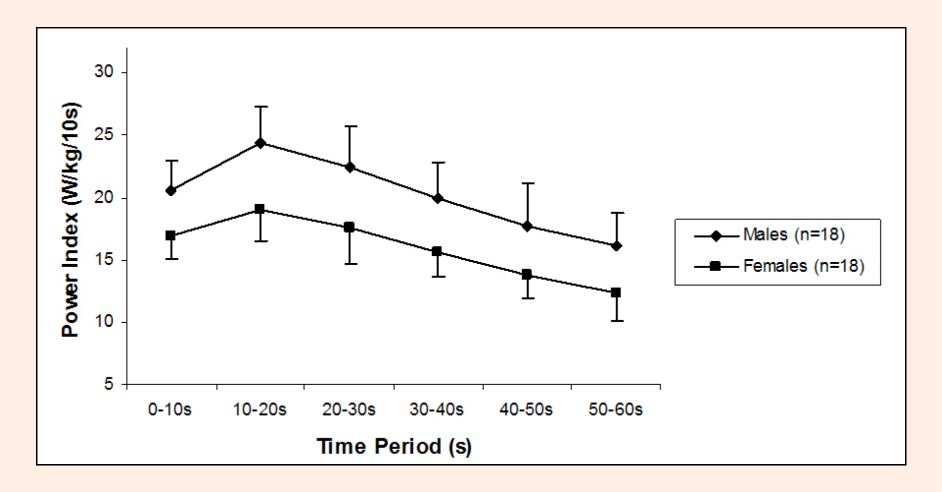

Figure 1. **10 s interval mean (SD) power indexes males vs females figure skaters pairs skaters.**

time-intervals are shown in Table 1.

Table 1. **Comparison of male and female pairs figure skaters and time intervals: 95% confidence intervals of power index (W/kg).**

	95% Confidence Limits	
Time Interval	Male	Female
0-10 s	10.5-21.6	15.9-17.9
10-20 s	23.1-25.7	17.7-20.4
20-30 s	20.9-23.9	16.1-19.0
30-40 s	18.7-21.1	14.6-16.9
40-50 s	16.5-19.1	12.5-15.1
50-60 s	14.9-17.3	11.2-13.5

The derived multiple regression equation for pair rank prediction was: competitive pair rank = -50.043 + training age (-0.575) + mass (-0.308) + height (0.302) + power index 10-20s (-1.446) flight time Y intercept (232.926). The β weights were: training age (-0.354), mass (-0.973), height (0.762), average power index 10-20s (-1.053), flight time Y intercept (2.214). Pearson correlations between males and females resulted in the following: average power-index r = 0.22, flight time Y intercept $r = 0.46$, fatigue index $r = 0.14$, power-index 0-10 s $r = 0.47$, 10-20 s $r = 0.44$, 20-30 s $r = 0.11$, 30-40 s $r = 0.02$, 40-50 s $r = 0.10$, 50-60 s $r = 0.17$, age $r = 0.82$, training age $r = 0.66$, mass $r = 0.43$, and height $r = 0.49$.

Reliability of the angle data could be determined because of the ability to use the three jumps at each kinematic time-interval (0 s, 20 s, 40 s, 60 s) of the kinematic analyses. The reliability values (r) are shown in Tables 2 and 3. None of the RMANOVAs showed a statistically significant main effect for sex or the interaction (all $p > 0.05$). Regarding angular position, all but knee angular position during ascent showed statistically significant effects for kinematic time-interval. Hip angular velocity on ascent showed statistical differences across time but did not reach the Dunn-Sidak criteria for statistical differences by sex in spite of a p = 0.046 ($\eta^2 = 0.14$, power = 0.52). Tables 4 and 5 show the RMANOVA results for the kinematic time-intervals of the angular position and angular velocity. Figures 2-7 show the maximum (ascent) and minimum (descent) angular positions of each measured joint as achieved during the respective phases of the jumps and the peak angular velocity of each joint in the ascent (positive) and descent (negative) phases at 0, 20, 40, and 60 s.

Table 2. **Reliability of maximum upward jump trials angles and downward minimum landing trials angles.**

Time Interval	Hip (r)	95% CI	Knee (r)	95% CI	Ankle (r)	95% CI
			Maximum upward jump angle reliability			
0 s	.93	.88-.97	.83	.70-.92	.90	.83-.95
20 s	.95	.90-.97	.91	.83-.95	.91	.87-.95
40 s	.97	.94-.99	.94	.88-.97	.95	.91-.98
60 s	.87	.77-.94	.93	.87-.97	.92	.86-.96
			Minimum downward landing angle reliability			
0 s	.92	.84-.96	.81	.61-.91	.92	.84-.96
20 s	.96	.91-.98	.87	.72-.94	.92	.83-.96
40 s	.94	.88-.97	.80	.58-.91	.92	.82-.96
60 s	.97	.95-.99	.83	.64-.92	.91	.81-.96

CI = confidence interval

Table 3. **Reability of jump trials peak upward angular velocity and peak downward angular velocity.**

Time Interval	Hip (r)	95% CI	Knee (r)	95% CI	Ankle (r)	95% CI
			Peak upward jump angular velocity reliability			
0 s	.91	.83-.95	.85	.72-.92	.84	.72-.92
20 s	.86	.73-.93	.84	.70-.92	.82	.66-.91
40 s	.86	.75-.93	.92	.86-.96	.89	.80-.95
60 s	.81	.63-.91	.90	.81-.95	.83	.68-.92
			Peak downward jump angular velocity reliability			
0 s	.81	.65-.90	.77	.58-.88	.89	.80-.94
20 s	.90	.82-.95	.56	.19-.77	.86	.74-.93
40 s	.85	.72-.92	.83	.69-.91	.78	.56-.89
60 s	.84	.71-.92	.77	.58-.88	.73	.51-.86

CI = confidence interval

Discussion

The results of this study show statistically different power-indexes for male and female pairs. The differences persisted across all test-time intervals. The relationships between pairs showed moderately strong and strong correlations, as defined by (Hopkins, 2002), between male and female figure skaters pairs in age, training age, flight time Y intercept, mass, height, and the first 20 s time-intervals of the repeated jump test. These analyses show

Table 4. Repeated measures ANOVA results for angular position and time interval.

Joint	$F_{(df)}$	Sig	Partial η^2	Power	KTI	95% CI
Jump ascent maximum angular position						
Hip	$19.8_{(3,84)}$	<.001	.41	1.0	0 s	168.5 to 174.4
					20 s	165.3 to 171.2
					40 s	162.8 to 170.0
					60 s	162.8 to 167.7
Knee	$2.1_{(2.12,84)}$*	=.130	.07	.43	0 s	180.9 to 183.8
					20 s	181.9 to 185.1
					40 s	181.9 to 185.0
					60 s	181.8 to 184.8
Ankle	$9.3_{(2.02,84)}$*	<.001	.25	.97	0 s	155.2 to 160.5
					20 s	156.1 to 161.3
					40 s	153.7 to 158.7
					60 s	152.0 to 156.8
Jump descent minimum angular position						
Hip	$8.7_{(3,84)}$	<.001	.28	.99	0 s	69.2 to 81.4
					20 s	63.0 to 75.2
					40 s	65.3 to 76.9
					60 s	63.1 to 74.8
Knee	$16.2_{(3,84)}$	<.001	.37	1.0	0 s	86.2 to 92.6
					20 s	83.3 to 89.7
					40 s	88.1 to 93.7
					60 s	90.2 to 96.2
Ankle	$12.0_{(3,84)}$	<.001	.30	1.0	0 s	87.0 to 91.9
					20 s	87.5 to 92.1
					40 s	89.3 to 94.0
					60 s	90.7 to 95.1

Sig = statistical significance, CI = confidence interval, * = violation of sphericity assumption and Greenhouse-Geisser adjustment to degrees of freedom (df)

that figure skaters pairs were relatively more similar in short-term as opposed to long-term power indexes. The power index results were comparable to male and female gymnasts studied previously (McNeal et al., 2010). After 20 s of the repeated jump test the figure skaters pairs power-indexes rapidly and systematically declined, regardless of sex. The most powerful predictive variables, based on *β* weights, were power-index variables from the 10-20 s time-intervals and the Y Intercept of flight-time.

Reliability analyses of the kinematic angle and angular data showed moderate to strong reliability values (George and Mallery, 1995). Males and females showed

Table 5. Repeated measures ANOVA results for angular velocity and time interval.

Joint	$F_{(df)}$	Sig	Partial η^2	Power	KTI	95% CI
Jump ascent maximum angular position						
Hip	$53.35_{(2.3,84)}$*	<.001	.66	1.0	0 s	407.9 to 445.5
					20 s	395.1 to 429.2
					40 s	359.1 to 389.4
					60 s	325.0 to 350.6
Knee	$76.1_{(2.17,84)}$*	<.001	.73	1.0	0 s	571.5 to 626.3
					20 s	560.6 to 601.9
					40 s	516.5 to 552.6
					60 s	454.6 to 486.3
Ankle	$39.7_{(2.31,84)}$*	<.001	.59	1.0	0 s	485.8 to 543.2
					20 s	467.9 to 510.4
					40 s	428.2 to 473.4
					60 s	392.3 to 430.8
Jump descent minimum angular position						
Hip	$15.6_{(3,84)}$	<.001	.36	1.0	0 s	-394.8 to -350.4
					20 s	-364.3 to -325.9
					40 s	-353.8 to -316.4
					60 s	-335.8 to -300.0
Knee	$37.0_{(3,84)}$	<.001	.57	1.0	0 s	-447.1 to -410.1
					20 s	-427.4 to -402.0
					40 s	-406.0 to -379.1
					60 s	-369.1 to -339.6
Ankle	$13.5_{(1.89,84)}$*	<.001	.33	1.0	0 s	-537.2 to -461.9
					20 s	-499.9 to -445.9
					40 s	-475.5 to -424.4
					60 s	-434.8 to -382.0

Sig = statistical significance, CI = confidence interval,* = violation of sphericity assumption and Greenhouse-Geisser adjustment to degrees of freedom (df).

changes in jumping techniques via joint kinematics, as represented by the angular positions and velocities of lower extremity joints. Male and female kinematic data largely showed parallel changes as fatigue accumulated and jumping techniques could not compensate (Figures 2-7). The declining angular velocities shown in this study were mirrored by muscle activation changes in a previous study (McNeal et al., 2010). The relative angles of this study contrasted with the earlier study that showed greater hip flexion angle in males when compared to females, and knee flexion increased with time in females and was greater overall. The earlier study showed agreement in the declining angular velocities and greater ranges of motion in angular positions over time (McNeal et al., 2010).

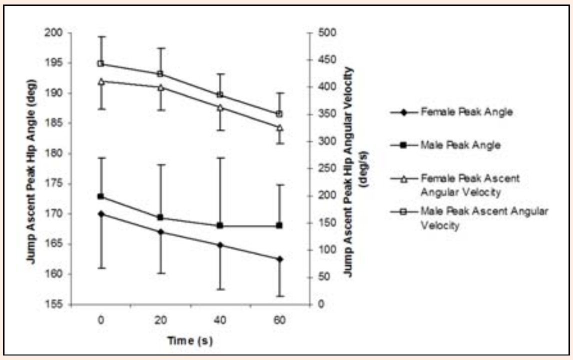

Figure 2. **Hip ascent angle kinematics.**

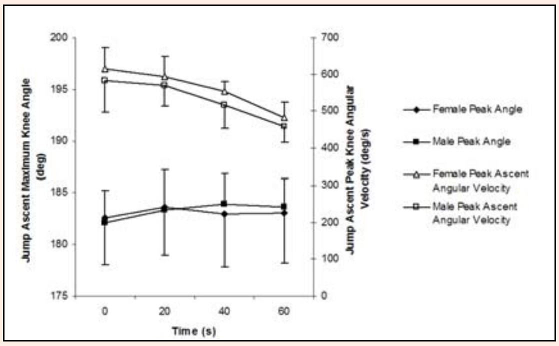

Figure 3. **Knee ascent angle kinematics.**

Generally, the effects of repeated jump test efforts are reduced peak force, decreased knee and ankle stiffness, reduced flight-time, and increased ground-time (Comyns et al., 2011; Kuitunen et al., 2002; Morio et al., 2011). Stretch-shortening cycle fatigue has been attributed to changes in the myotatic stretch reflex because of observation of declining knee eccentric forces and muscle stiffness combined with decreased reflex sensitivity, but other factors are also active and complicate the interpretation of stretch-shortening cycle fatigue (Nicol et al., 2006). Force-time curves collected during repeated jump tests showed reduced peak forces, at 40 s compared to a control jump, and later peak forces continued to decline through the remainder of the repeated jump test. Stretch-shortening cycle fatigue tends to be expressed in both acute (increased muscle activation during braking) and delayed (increased muscle activation during push off) fashions (Requeme et al., 2005). Eccentric tension has been shown to elicit sensitive changes in voltage-gated sodium ion channels and related proteins during fatiguing stretch-shortening cycle activity that may account for the cellular mechanism of altered behavior during stretch-shortening cycle fatigue states (Piitulainen et al., 2008).

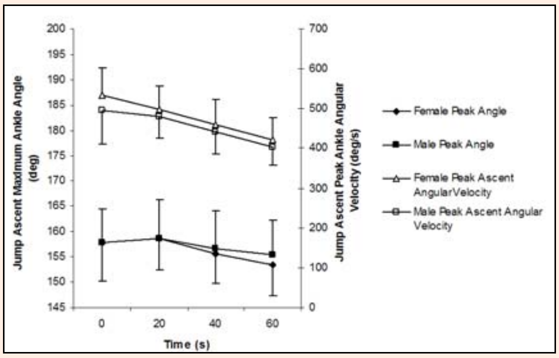

Figure 4. **Ankle ascent angle kinematics.**

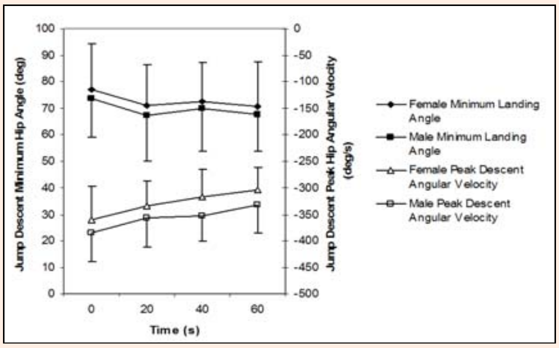

Figure 5. **Hip descent angle kinematics.**

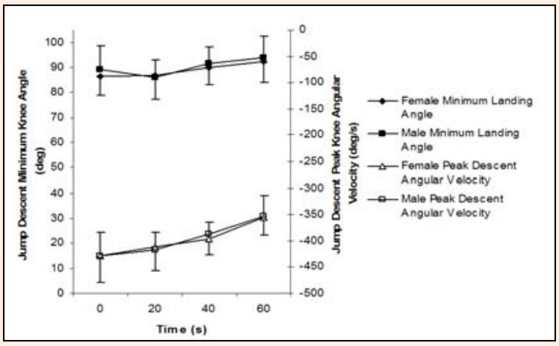

Figure 6. **Knee descent angle kinematics.**

In practical terms, fatigue and recovery due to stretch-shortening cycle appears to be different from concentric-only exercise. Concentric-only exercise and recovery are controlled predominantly by metabolic processes, while stretch-shortening cycle fatigue is more complex, indicating different motor control strategies using variable muscle stiffness and activation (Horita et al., 2003). Moreover, the stretch-shortening cycle is an important tool to study fatigue (Komi, 2000). For example, stretch-shortening cycle fatigue appears to influence both extrafusal and intrafusal muscle, which may describe a form of neural fatigue (Avela and Komi, 1998; Avela et al., 1999; Gollhofer et al., 1987). The inclusion of neural fatigue considerations in figure skaters training may open a productive line of research to identify and to characterize neural contributions to the fatigue-related decline in long-term skating programs with difficult jumps.

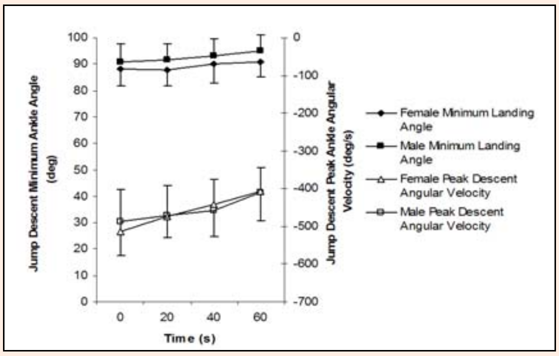

Figure 7. Ankle descent angle kinematics.

Conclusion

The repeated jump test and other variables in this study showed a combined strong relationship with the National Team Rankings and statistical differences in the repeated jump test Power-Indexes by sex and 10 s time-intervals. Approximately 50% of the variability in pair Ranks could be predicted by knowing the size, experience, and 10-20s power indexes of these highly trained athletes. As such, the ability to predict 50% of the variance in ranks of these skaters indicates that the stretch-shortening cycle and stretch-shortening cycle-related fatigue are probably crucial factors in figure skaters' performance. Results indicated that sustained jumping power was comparable between male and female pairs through the first third of the repeated jump test, but varied more in the latter periods. Kinematic analyses indicated that angular positions and velocities of lower extremity joints paralleled declines in the repeated jump test power index.

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Key points

- The repeated jumps test can account for about 50% of the variance in pairs ranks.
- Changes in technique are largely due to fatigue, but the athletes were able to maintain a maximum flexion knee angle very close to the desired 90 degrees. Changes in angular velocity and jump heights occurred as expected, again probably due to fatigue.
- As expected from metabolic information, the athletes' power indexes peak around 20s and decline thereafter. Coaches should be aware of this time as a boundary beyond which fatigue becomes more manifest, and use careful choreographic choices to provide rest periods that are disguised as less demanding skating elements to afford recovery.
- The repeated jumps test may be a helpful off-ice test of power-endurance for figure skaters.

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