INVITED REVIEW

Performing Triple and Quadruple Figure Skating Jumps: Implications for Training

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Abstract/Résumé

The purpose of this paper is to review the biomechanics of triple and quadruple figure skating jumps, focusing on information that has implications for strength and conditioning programs. At a minimum, to complete the required revolutions in a jump, a skater must balance the average angular velocity with the time in the air. Vertical velocity at takeoff is similar in high revolution jumps to that in low revolution jumps; however, when comparing skaters of different abilities, those with higher abilities generate greater vertical velocities at takeoff for the same type of jump. Powerful extension of the legs is the primary factor in generating vertical velocity. Some jumps use asymmetrical extension of both legs, while other jumps involve extension of only one leg. Angular velocity is controlled primarily by the skater's moment of inertia, which means skaters must forcefully arrest the motion of the arms and legs after the propulsion phase and then quickly position the arms and legs close to the axis of rotation during flight. Training exercises that emphasize eccentric and concentric muscle actions and which are adaptable to asymmetrical or unilateral motions, such as box jumps and medicine ball throws, are a crucial component to off-ice training programs for figure skaters.

Cet article présente le bilan de la biomécanique des figures multiples (triple et quadruple) en patinage artistique en mettant l'accent sur les éléments d'information utiles aux

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programmes de mise en forme et d'amélioration de la force musculaire. À tout le moins, le patineur doit d'abord ajuster sa vélocité angulaire moyenne au temps de suspension afin de compléter le nombre de révolutions requis. La vélocité verticale à l'appel est la même quel que soit le nombre de révolutions; quand on compare des patineurs de diverses aptitudes, les patineurs plus habiles génèrent plus de vitesse verticale à l'appel d'une même figure. Une puissante extension des membres inférieurs est le facteur-clé d'une bonne vélocité verticale. Certains sauts requièrent une extension asymétrique des deux jambes et d'autres ne requièrent que l'extension d'une seule jambe. La vélocité angulaire dépend essentiellement du moment d'inertie généré par le patineur; en d'autres mots, le patineur doit systématiquement stopper le mouvement des bras et des jambes à la suite de la phase de propulsion et doit rapidement ramener bras et jambes le plus près possible de l'axe de rotation du corps durant la suspension. Pour s'entraîner en dehors de la patinoire, il faut absolument élaborer des programmes d'entraînement basés sur des actions miométriques et pliométriques adaptées à des mouvements asymétriques et unilatéraux tels les sauts en contrebas et des lancers de ballons lestés.

Introduction

Figure skating is a sport that combines athletic prowess with elegant artistry. Skaters are required to combine diverse skills such as jumps, spins, step sequences, and spirals into a seamless program which has both technical difficulty and beautiful presentation. As the sport of figure skating has developed over the years, the athletic capabilities of the athletes have increased, due in part to improved training and equipment, as is true in many sports. With the increased athleticism in skating have come increased levels of difficulty in the technical elements, such as jumps and spins.

Today's male singles skaters are required to complete 3 jumps in their short programs, one of which must be a triple or quadruple jump. In their free skating program, male skaters may complete up to 8 jumps. Of these 8 jumps, the skaters competing at the highest level of international competition will complete entirely triple and quadruple revolution jumps. Today's female skaters also must complete 3 jumps in their short programs, one of which must be a triple jump. In their free programs, female skaters may complete up to 7 jumps. Of these 7 jumps, female skaters successfully competing at the international level will have almost entirely triple jumps and triple combination jumps (U.S. Figure Skating, 2004).

Up-and-coming skaters hoping to break into the national or international scene must master these skills as they prepare for the increasing levels of difficulty that are likely to emerge as the envelope of athletic performance expands even further. To master this degree of technical difficulty, the skaters must continue to make advances in their physical capabilities such as flexibility, strength, and power. Understanding the biomechanics of skating skills can help skaters and their coaches design effective sport-specific training programs to achieve this goal. Thus, the purpose of this paper is to review the biomechanics of triple and quadruple figure skating jumps, specifically focusing on information that has implications for strength and conditioning programs.

Basic Mechanics Behind Skating Jumps

At a minimum, to complete the required revolutions in a jump, a skater must balance the average angular velocity with the time in the air. While this will not guarantee a successful jump, as there are other technical requirements and factors, it is an essential component of a successful jump. The time in the air will depend on the vertical velocity at the instant of takeoff. Vertical velocity is generated during the propulsive phase of the jump (Figure 1) as the skater applies downward forces to the ice. Time in the air can also be affected by the skater's landing position. Recent studies have shown that skaters land with their center of mass in a lower position than at takeoff (King et al., 2004). When a skater "delays" the landing with slightly flexed hips, knees, or ankles, as opposed to more extended hips, knees, and ankles, he or she gains a few hundredths of a second of flight time. While this may not sound like a significant increase in time, depending on the skater's rotational velocity it could result in an extra 10 to 20 degrees of rotation. In some instances this could be the one factor that makes the difference between being able to land the jump or not.

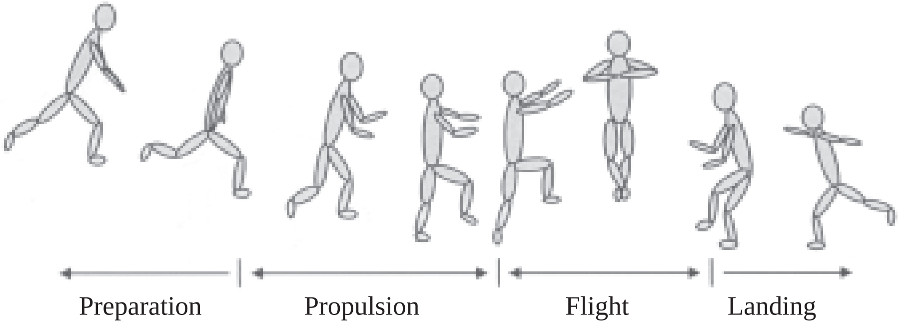

Figure 1. Depiction of an axel showing the phases of a figure skating jump. The approach phase, not depicted, precedes the preparatory phase.

The skater's average angular velocity during the flight phase of the jump will depend on his or her angular momentum during flight and his/her moment of inertia. Angular momentum is a measure of the skater's angular motion about the axis of rotation. The axis of rotation refers to the skater's instantaneous axis of rotation as determined by the orientation of the principal axis of inertia of the minimal moment of inertia. However, few if any published studies have actually reported angular momentum about this axis; instead, researchers have used either the vertical axis (e.g., Albert and Miller, 1996) or the longitudinal axis of the skater based on the orientation of the trunk (e.g., King et al., 2002a).

Angular momentum is the product of moment of inertia and angular velocity and is constant during the flight phase of a jump. Torque is applied to the ice during the approach, preparatory, and propulsive phases of a jump so as to produce angular momentum for the flight phase. Once in the air, since angular momentum is constant, the angular velocity of the skater can be changed only by changes to his or her moment of inertia. Moment of inertia is manipulated by the skater as the arms and legs are positioned closer to or farther from the axis of rotation. Specifically, if the skater's moment of inertia increases (masses of arms and legs positioned farther from the axis of rotation), the angular velocity will decrease; and if the skater's moment of inertia decreases (masses of arms and legs positioned closer to the axis of rotation), the angular velocity will increase.

Thus there are three main mechanical components that contribute to the skater's achieving the correct balance of time in the air and rotational velocity: (1) generating appropriate levels of downward force during propulsion; (2) generating appropriate levels of torque during approach, preparation, and propulsion; and (3) controlling the moment of inertia (body position) during the flight phase of the jump. To link these three components to important muscle groups and strength and conditioning needs, the specific biomechanics of the different jumps must be analyzed.

Biomechanics of Specific Jumps

In the past, most of the research on the biomechanics of figure skating jumps has focused on the axel jump (Albert and Miller, 1996; Aleshinsky et al., 1988; King et al., 1994). However, one of the most original biomechanical studies ever completed was done on waltz, salchow, toe-loop, and flip jumps (Aleshinsky, 1986). Recently several studies have been conducted on triple Lutzes (King et al., 2001; 2002a) and quadruple toe-loops (King et al., 2002b; 2002c; 2004). The majority of these studies are purely descriptive in nature, providing a biomechanical description of the technique used by national caliber novice, junior, or senior skaters to complete the respective jumps. A few studies, however, make comparisons between skaters of different levels or between different types of jumps in order to identify critical factors related to completing triple and quadruple jumps. Specifically, King et al. (1994) and King (1997) compared single, double, and triple axels of junior and senior level skaters; Albert and Miller (1996) compared single and double axels of "good" figure skaters; and King et al. (2004) compared triple and quadruple toe-loops of 2002 Olympic male competitors.

When examining the information available from all these studies, several important biomechanical factors related to completing multi-revolution jumps emerge. Vertical velocity at takeoff is similar in higher revolution jumps as compared to lower revolution jumps (Table 1) (Albert and Miller, 1996; King et al., 1994; 2002c). However, when the same jump, such as a double axel, is compared across skaters of different abilities, those of higher ability who have mastered higher revolution jumps (triple as compared to double) generate greater vertical velocity at takeoff (Table 2).

Few studies have reported angular momentum values across groups of skaters or jump types. Albert and Miller (1996) reported similar angular momentum values for single and double axels of 16 "good" skaters, while Aleshinsky et al. (1988) reported greater angular momentum for a triple axel as compared to a double axel of an Olympic medalist. Obviously there is a need for more research in this

Table 1 Vertical Takeoff Velocities ($M \pm SD$) for Low and High Revolution Jumps Performed by the Same Skaters

	Vertical Takeoff Velocity (m/s)	
5 Elite male skaters[1]	Double axel	Triple axel
	3.4 ± 0.3	3.3 ± 0.2
8 Good male skaters[2]	Single axel	Double axel
	2.6 ± 0.1	2.6 ± 0.1
8 Goodfemale skaters[2]	Single axel	Double axel
	2.3 ± 0.1	2.4 ± 0.1
6 Olympic male skaters[3]	Triple toe loop	Quad toe loop
	3.2 ± 0.4	3.3 ± 0.2

Note: Data are from: [1]King et al., 1994; [2]Albert and Miller, 1996; [3]King et al., 2002b, 2002c.

Table 2 Vertical Takeoff Velocities ($M \pm SD$) for Same Jump Types Performed by Skaters of Differing Abilities

	Vertical Takeoff Velocity (m/s)	
Double axel	Good skaters[2]	Elite skaters[1]
	(cannot do triple axel)	(can do triple axel)
	2.6 ± 0.1	3.4 ± 0.3
Triple toe loops[2]	Elite skaters[3]	Elite skaters[3]
	(cannot do quad toe loop)	(can do quad toe loop)
	3.0 ± 0.1	3.3 ± 0.2

Note: Data are from: [1]King et al., 1994; [2]Albert and Miller, 1996; [3]King et al., 2002b, 2002c.

area. However, despite the disparate findings in terms of angular momentum, the average rotational velocity systematically increases as number of revolutions increases (Albert and Miller, 1996; Aleshinsky, 1986, Aleshinsky et al., 1988; King, 1997; King et al., 1994; 2004).

This increase in angular velocity is accompanied by decreases in moment of inertia at takeoff and during flight (Albert and Miller, 1996; Aleshinsky, 1986; King et al., 2002c), suggesting that the primary determinant of angular velocity during flight in a figure skating jump is moment of inertia which is controlled by the skater's body position (Table 3). Thus it appears that three primary conclusions

Table 3 Angular Momentum and Moment of Inertia ($M \pm SD$) at Takeoff for Single and Double Axels Performed by the Same Skaters

	Takeoff Angular Momentum (kgm^2/s)		Takeoff Moment of Inertia (kgm^2)	
	Single axel	Double axel	Single axel	Double axel
8 Good male skaters	28.6 ± 8.8	29.6 ± 11.1	4.3 ± 1.1	3.7 ± 1.1
8 Good female skaters	16.5 ± 3.1	16.2 ± 2.9	2.9 ± 0.8	2.5 ± 0.6

Note: All data are from Albert and Miller, 1996.

can be drawn regarding biomechanics of figure skating jumps: as skaters add more revolutions to their jumps, they develop techniques to (a) generate greater vertical velocity at takeoff, (b) generate similar or greater angular momentum at takeoff, and (c) decrease moment of inertia at takeoff and during flight.

GENERATING VERTICAL VELOCITY

Vertical velocity is developed during the propulsive phase of the jump during which the skater forcefully and powerfully extends the hip, knee, and to some extent the ankle, creating downward forces against the ice. Depending on the jump type, these forces may come solely from a single takeoff leg or from an asymmetrical extension of both legs (Figure 2). The actual range of motion of the joints varies from skater to skater and jump to jump; though for pick jumps the knee of the pick leg typically extends from 40 or 50 degrees of flexion to 10 deg of flexion, while the knee of the glide leg may extend from 60 or 90 deg of flexion to 20 deg of flexion (King et al., 2001; 2002b). The duration of the propulsion phase has rarely been reported, but from examining published graphs, a propulsion phase just under 0.2 seconds is typical for triple lutzes and quadruple toe-loops (King et al., 2002a; 2002c). The propulsive phase of the jumps is preceded by eccentric muscle contractions, suggesting that use of the stretch shortening cycle is an important component to generating vertical velocity (King et al., 2002c). Thus it is important for skaters to incorporate plyometric exercises such as box or depth jumps, which elicit the stretch shortening cycle, into their off-ice training program.

In most figure skating jumps there is little or no relative contribution to total body vertical momentum from the upward motion of the free limbs (King et al 2002a; 2002c; 2004). In any type of jump, upward motion of the free limbs affects the forces applied to the ice during takeoff and has the potential to increase the impulse generated during the takeoff. In the axel jump, the movements of the free limbs (both arms and the non-takeoff leg) sufficiently contribute to the impulse during takeoff to account for 8 to 10% of the vertical momentum of the total body (King, 2004). The motion of the trunk is another important contributor to the forces developed and thus the impulse generated during takeoff. Due to the large mass of

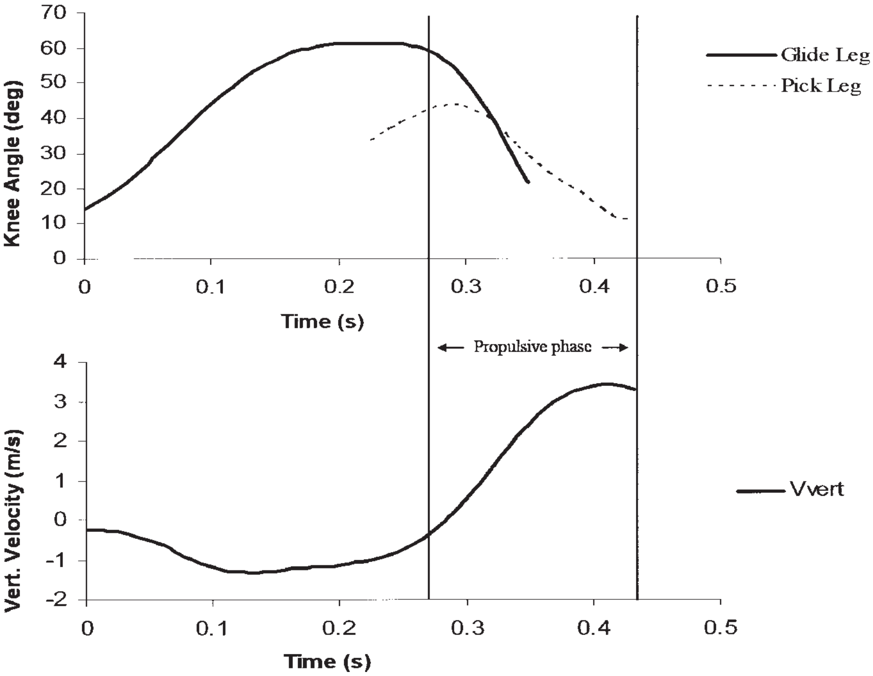

Figure 2. Top graph shows the glide and takeoff leg knee angle through the preparation and propulsive phase of a quad toe-loop. A zero degree angle is fully extended. Bottom graph shows the vertical velocity of this skater's center of mass through the same phases.

the trunk, the extension motion of the trunk during takeoff is an essential component of total body vertical momentum for figure skating jumps.

GENERATING ANGULAR MOMENTUM

As the skater approaches the jump takeoff, the forces generated from the movements of the skater's body and limb segments also create a torque about the axis of rotation. This torque provides angular impulse to the skater about the axis of rotation which creates angular momentum. Albert and Miller (1996) reported that in the axel jump, the movement of the skater's free leg during the approach and propulsive phases provided the largest contribution of all segments to the total body angular momentum. As the skater is on the forward outside edge and brings the free leg through during the propulsive phase, the torque about the axis of rotation increases, causing an increase in angular momentum. However, just prior to takeoff, as the free leg nears maximum hip flexion, the contribution of the leg to angular momentum begins to decrease due to its deceleration. At this point the arm motions, resulting from flexion of the shoulders, assist in creating positive angular impulse. However, the contribution of the arms is not sufficient to maintain a constant angular momentum, due to the decreasing contribution of the free leg. Thus the total body angular momentum decreases slightly just before takeoff.

For the triple lutz, King et al. (2002a) reported that movements of the arms were more influential than those of the legs in creating angular impulse during the propulsive phase, and thus had a greater effect on the generation of total body angular momentum. King et al. reported that the angular momentum was primarily generated prior to toe-pick as the skater brought the left arm back and up (horizontal abduction), the right arm forward and in (flexion and adduction), and rotated and extended the trunk. These motions, as the skater maintained a back outside edge, created angular impulse about the axis of rotation which in turn provided angular momentum for the jump.

CONTROLLING MOMENT OF INERTIA

A distinguishing characteristic of multi-revolution jumps, as compared to single revolution jumps, is a smaller moment of inertia about the axis of rotation prior to takeoff and/or during flight (Albert and Miller, 1996; Aleshinsky, 1986; King et al., 2004). The smaller moments of inertia are from a closer position of the arms and free leg to the axis of rotation (King et al., 2002c). Adopting a smaller moment of inertia prior to takeoff mechanically limits the skater’s ability to dramatically increase angular velocity during flight, as detailed by Aleshinsky (1986), but it does enable skaters to increase angular velocity while still on the ice, which in turn results in greater angular velocity at the instant of takeoff. Once in the air, skaters continue to decrease their moment of inertia, though the magnitude of the decrease depends greatly on jump type.

Once skaters have reached the minimum moment of inertia obtainable based on their body size, they can no longer attain higher angular velocities by decreasing their moments of inertia, as they are already in their tightest possible rotating position. In the long run, this strategy of relying almost solely on smaller moments of inertia to increase angular velocity as number of revolutions increases is limiting to the continued progression of completing higher and higher revolution jumps in the sport of figure skating. It is a successful strategy for the jumps currently being performed, however, and is consistently used by figure skaters completing multi-revolution jumps.

Implications for Training

As the majority of biomechanical analyses have focused on jump takeoffs, versus landings, the training implications discussed herein will focus on the takeoff phase of the jump. This is not to imply, however, that the landing is less important. In fact it is imperative that off-ice training programs include exercises specifically aimed at (a) strengthening the abdominals and trunk muscles, such as exercises with a medicine ball and abdominal curls and side curls on a stability ball; (b) training the leg muscles eccentrically for landing, such as box landings and lateral bench jumps; and (c) training balance, such as single leg squats on a stability disk and balancing on a wobble board while imitating the landing motion of the free leg.

For the takeoff phase of figure skating jumps, concentric extension of the hip, knee, and ankle, preceded by large eccentric contractions of the extensor muscles, are critical motions in generating vertical velocity during figure skating jumps. Thus when doing jump-specific training, skaters need to focus on the extensor muscle groups of the lower extremity, such as gluteus maximus, quadriceps, hamstrings, adductor magnus, and gastrocnemius during contractions in both the eccentric and concentric directions. In lutz and toe-loop jumps, it is known that both legs contribute to the generation of vertical velocity, though the motion is not symmetrical either in range of motion or timing. The glide leg extends first and goes through a larger range of motion, followed by the extension of the pick leg through a smaller range of motion. In the axel the takeoff is entirely from one leg. This suggests that traditional hip and knee extensor exercises, such as squats, should be adapted to more closely represent the biomechanics of the takeoff of skating jumps.

Skaters can use light resistance such as dumbbells or sport cords and focus on fast powerful movements. For example, they can perform squats with dumbbells, emphasizing speed of movement as they explode upward. Lunges can be performed with light hand weights with the skater lunging forward or to the right and left on a diagonal. Box jumps, power skips, and squat jumps on a rebounder are also effective techniques to train these muscles using concentric and eccentric contractions at high speeds. These plyometric exercises evoke the stretch shortening cycle, which is a critical component of the figure skating jump takeoff.

Skaters will need to do both unilateral (e.g., single-leg box jumps) and bilateral (e.g., double-leg box jumps) exercises. When doing bilateral exercise they can vary the leg positions to better approximate the asymmetrical motions used in skating. For example, a double-leg box jump can be performed with the right foot slightly forward of the left foot, or vice versa, as the skater explodes upward off the floor. Additionally, the skater can incorporate diagonal and lateral box jumps. For the axel jump, jump-specific training should include training of the hip and shoulder flexors and abductors, both in the concentric and eccentric directions, as these motions make an important contribution through the free limbs in generating vertical velocity. In fact, Polensky et al. (1990) identified shoulder abductor strength and knee extensor strength as two of the main predictors of jump height in figure skating. Medicine ball throws with and without twisting, box push-ups, and sit-up medicine ball throws with and without twisting are three good ways to train the upper body using concentric and eccentric muscle actions at high speeds.

There are several additional reasons why upper body strength and power are critical to successful jumping in figure skating and should be incorporated into off-ice training programs. Arm movements contribute to the production of angular momentum during takeoff and are crucial to decreasing the moment of inertia during takeoff and flight. To position the arms and limbs close to the body, skaters must resist the tendency of the limbs to continue moving in a linear path as they are pulled around in a circle. These inertial forces increase with number of revolutions, amplifying the need for increased strength to complete these skills with the arms in a flexed position close to the body (Aleshinsky et al., 1988).

The motions used during takeoff to generate angular impulse and then position the arms and legs close to the axis of rotation depend on jump type. For all jumps, however, the elbows go through flexion during the propulsive phase to bring the hands toward the chest. The shoulder motions, in addition to varying with jump type, also vary from the right to left sides of the body. In the lutz for example, the left arm often is typically brought above the head during propulsion and then must be brought down to the rotating position using shoulder extension and adduction. The right shoulder meanwhile has typically gone through shoulder flexion and adduction (King et al., 2001).

Thus, muscles such as the biceps, pectoralis, deltoid, and latissimus dorsi which are active in shoulder flexion, abduction, horizontal adduction, and extension are important for positioning the arms during the propulsive and fight phases. However, typical upper body exercises, such as a bench press, will not meet the skater's specific needs since these are often symmetrical bilateral exercises. Instead, or in addition, skaters will want to incorporate asymmetrical arm exercises into their jump-specific resistance training program. For example, skaters can use a sport cord to provide resistance during arm pull-ins during which they replicate the arm motions used in the takeoff of each jump. Medicine ball throws with a twisting motion (being sure to do repetitions in each direction) are again a good exercise for skaters because they utilize asymmetrical arm motions.

The leg and arm motions that contribute to decreased moments of inertia in higher revolution jumps are often abbreviated motions of the same movements observed during lower revolution jumps. For example, in the triple axel, a quick but short hip flexion range of motion is used as compared to the larger hip flexion range of motion during the double axel. There are obvious strength implications for the ability to abruptly stop the hip flexion motion at the end of the propulsion phase. Training these eccentric contractions for both the arm and free leg motions may be an area for improvement in a skater's jump-specific training program. Both upper and lower body plyometric exercises such as box push-ups, box jumps, and power skipping are good exercises for training these motions.

Conclusion

Over the years, figure skaters have increased the level of technical difficulty in their programs. Improvements have been made in off-ice strength and conditioning with growing emphasis on the importance of core and upper body strength. A thorough examination of the role of the upper and lower body to the vertical and rotational components to skating jumps, however, has not been addressed. Specifically, this review has examined jump takeoffs, though the landings of jumps are equally important. Extension of the takeoff leg is critical to generating vertical velocity; in many jumps both legs contribute to the generation of vertical velocity and the motion is asymmetrical.

In the jumps studied to date, countermovements are incorporated into the jumping technique, highlighting the use of the stretch shortening cycle in figure skating jump takeoffs and the need to incorporate eccentric and plyometric exercises into off-ice training. In some jumps the arms have a meaningful contribution to vertical velocity of the skater, though in most jumps the arm motion is more critical to the rotational component of the jump. Due to the different arm motions of the various jump takeoffs, skaters should not limit themselves to single joint exercises, nor should they rely solely on bilateral symmetrical resistance training exercises.

Examples of good upper body exercises are arm pull-ins with sport cord and medicine balls throws with and without twisting. The medicine ball throws are also good explosive exercises for developing core musculature. Medicine ball throws can be done standing and utilizing a sit-up motion on or off a stability ball. Good lower body exercises include box jumps with one and two legs, power skips, and lunges performed straight and on the diagonal. While this review has emphasized jump-specific training, it is important to remember that there is much more to skating than jumping. As with any athlete, skaters should incorporate general strength, flexibility, core strength, and balance into their overall training program.

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