

ABSTRACT

PARADIS, S. A. The relationship between knee joint angle, stretch-shorten cycle performance, and jump distance in ski jumping. MS in Exercise and Sport Science – Human Performance, August 2000, 25pp. (C. Foster)

This investigation examined the relationship between knee angle, stretch-shorten cycle performance, and jump distance in ski jumping. 44 elite ski jumpers were video taped at 120 Hz. Hip, knee, and ankle displacements were digitized to examine the relationship between the knee joint angle, stretch-shorten cycle performance, and jump distance in ski jumping. Jump distance was recorded for comparison. Average distance jumped was 99.03 ± 11.6 m. During the stretch-shorten cycle movement, the average amount of knee flexion was -6.6 ± 3.9 ° and the average amount of knee extension was 8.8 ± 4.8 °. A significant ($p = 0.014$) quadratic relationship was found between the amount of knee flexion and jump distance. The knee-joint extension velocity averaged 9.2 ± 0.8 radians/s, but was not found to be significantly related to jump distance. The quadratic relationship between jump distance and the amount of knee joint flexion demonstrated an optimal knee flexion range for maximizing jump distance. This study suggests that when elite jumpers utilize an optimal stretch-shorten movement, in combination with proper form on the take-off table and in the air, they produce longer jump distances.

**THE REALTIONSHIP BETWEEN KNEE JOINT ANGLE, STRETCH-SHORTEN
CYCLE PERFORMANCE, AND JUMP DISTANCE IN SKI JUMPING**

**A MANUSCRIPIT STYLE THESIS PRESENTED
TO
THE GRADUATE FACULTY
UNIVERSITY OF WISCONSIN-LA CROSSE**

**IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
MASTER OF SCIENCE DEGREE**

**BY
SETH A. PARADIS
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AND TEACHER EDUCATION
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THESIS FINAL ORAL DEFENSE FORM

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We recommend acceptance of this thesis in partial fulfillment of this candidate's requirements for the degree:

Master of Science in Exercise and Sport Science – Human Performance

The candidate has successfully completed the thesis final oral defense.



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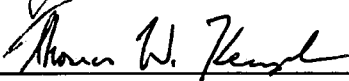
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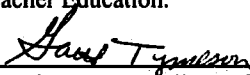


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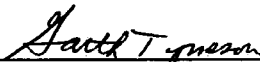
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This thesis is approved by the College of Health, Physical Education, Recreation, and Teacher Education.



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INTRODUCTION

Biomechanical analysis of ski jumping dates back to 1927 (Strauman, 1927). Ski jumping is a very complex skill involving several phases such as the inrun, take-off, flight, and preparation for landing. Each phase has importance to the length of the jump (Komi & Virmavirta, 1996). The take-off phase requires a high level of both physical and technical performance. The athlete performs a movement that requires extension of the hip and knee joints to produce a negative aerodynamic effect (Antonio & Renato, 1987).

The take-off and flight phases of ski jumping has been the subject of a variety of studies (Hubbard, Hibbard, Yeadon, & Komor, 1989; Tveit & Pederson, 1981). The majority of these studies have been conducted on joint velocities and forces involved in the take-off phase of ski jumping (Hubbard, et al., 1989; Tveit & Pederson, 1981). It is known that a stretch-shorten cycle (SSC) is used in most athletic events (Wilson, Wood, & Elliott, 1991); however, there is a lack of literature concerning the possible use of a SSC during ski jumping.

The performance of an eccentric muscular action followed immediately by a concentric action is a SSC movement (Wilson et al. 1991). Imposing a delay between the eccentric and concentric phases of a SSC movement reduces the observed augmentation to performance derived from the stretch. The reduction realized appears to be a function of the delay duration, with evidence supporting an exponential relationship with a 0.85 s half-life of decay (Wilson, 1991). This muscular pattern is apparent in running,

jumping, throwing, hitting, and lifting activities (Wilson, et al., 1991). Research demonstrates that there are a few positive reasons for the occurrence of SSC. These include neural augmentation, storage and utilization of elastic energy, two joint muscle energy transfer, and preload effect. Neural augmentation has been observed by Bosco, Tarkka, and Komi (1982). Subjects performed static jumps and countermovement jumps and all subjects demonstrated significant neural augmentation due to prior stretch. Jones and Watt (1991) suggested that the preactivation is programmed and dispatched from the dorsal stretch-reflex before landing. They stated that the correct timing of the jumping action and landing have been learned through previous experience. Avela, Santos, and Komi, (1994) expanded on this concept and suggested that the control of the landing is not solely regulated by the previous learning process, but is also influenced by the fast adaptation of the vestibular apparatus. They also suggest that the electrical activity prior to the ground contact is the most sensitive feature with respect to the various lead conditions.

The concept of storage and utilization of elastic energy has been reviewed by Labeit and Kolmerer (1995). They suggested that titin, a skeletal muscle protein, may act as two springs in series. Differential expressions of the springs provide a molecular explanation for the diversity of sarcomere length and resting tension in vertebrate striated muscles. Titin likely accounts for the intrinsic elasticity of vertebrate striated muscle myofibrils because degradation of titin by radiation or proteases or its removal by extraction results in a loss of passive tensions (Trinick & Tskhovrebova, 1999). Two joint muscle energy transfer may exist in the take-off technique. Appropriate movements of the joints and body segments should be aimed for because reaction force is the result

of the integrated kinetic parameters of each joint or segment (Virmavirta & Komi, 1989). Wilson (1991) demonstrated that the dominant view maintained by SSC researchers is that observed augmentation to concentric motion derived from prior stretch has neural origins. Komi (1987) agreed and demonstrated that the amount of preactivation increases with increasing running speed.

Take-off force is produced by joint movement (Virmavirta & Komi, 1989). Kinetic parameters can be determined by the analysis of the jump action (Sasaki, Tsunoda, & Uchida, 1993). The mean relative angle for the knee joint at the initiation of the take-off phase for elite international subjects (90.18°) was less than demonstrated by the jumpers from the U.S. (90.43°). This was directly related to the difference in position of the lower leg. The angle of the lower leg for the international group was 47.67° and the angle for the U.S. group was 50.15° . This represented a statistically significant difference (Sasaki, et al., 1993). The reduced angle of the lower leg and nearly identical positioning of the thigh indicated that the variability in the knee joint angle could be attributed to the positioning of the lower leg (Campbell, 1976). This suggests the importance of lower body joint angles in jump distance. However, little data are available concerning how these angles affect jump distance.

The purpose of this study was to investigate the relationship between the change in knee joint angle, representing the stretch-shorten cycle and the jump distance of elite ski jumpers. The hypothesis was that the stretch-shorten cycle would occur and result in a longer jump distance.

METHODS

Subject Selection

Forty-eight competitors were filmed during the first round of the Westby Continental Cup in Westby, Wisconsin on February 12, 2000. An average temperature of negative 5.6 ° C and average wind speed of 10 km were recorded during the collection of data. The subjects consisted of national and international elite jumpers on a L118 (K108) jump. The jumpers had a mean weight of 65 ± 5.2 kg, mean height of 176 ± 10 cm, and a mean ski length of 258 ± 8 cm. The population was chosen because of the subjects' high skill level in ski jumping. The Institutional Review Board for the Protection of Human Subjects at the University of Wisconsin-La Crosse approved the protocol.

Experimental Protocol

The take-off was examined as a two-dimensional motion of the subjects at take-off. The jumper's body and equipment were modeled as four sections: the upper body, thigh, lower leg, and ski (see Figure 1). This allowed hip (1), knee (2), and ankle (3) angular displacement to be measured. The change of the knee angle was used to determine the existence of a stretch-shorten cycle during the take-off motion. The competitors were filmed using a PEAK (Peak Performance Technologies, Incorporated, Englewood, CO) high-speed video camera (120 f/p/s) with the shutter speed set at $1/1000$ s. The camera was placed 12.7 m perpendicular to the take-off table. This camera view encompassed the last 8 m prior to takeoff. The video data collected were converted from VHS video to AVI files with the use of the IOMEGA BUZZ (Iomega Corporation, Roy, UT) video capturing software.

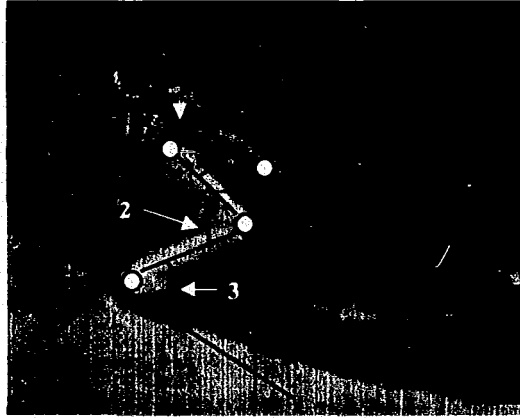


Figure 1. The 2-D model of the ski jumper.

The AVI files were digitized to calculate joint angles using the Video Expert II (Motion Analysis Corporation, Santa Rosa, CA) system at the University of Wisconsin-La Crosse. Video data were digitized on 44 jumpers during the trial round on February 12, 2000. Joint locations were estimated during digitization in accordance with the noninvasive video data collection style used by Arndt, Bruggeman, Virnavirta, and Komi (1995). Joint centers were estimated by locating anatomical landmarks on the jumpers. Hip, knee, and ankle angles were digitized for a series of 8 to 10 frames during the 8 m prior to takeoff. Raw data were used to calculate knee joint extension angular velocity. Jump distance was recorded following each jump. The competitors jumped in a predetermined order according to bib number. The predetermined order allowed the jump distance and motion analysis data to be correlated.

RESULTS

The average knee angle displacement was calculated by examining 44 subject's knee angles 8 m previous to the end of the take-off table. Figure 2 shows the percentage of knee angle displacement over a 0.165 s period prior to take-off.

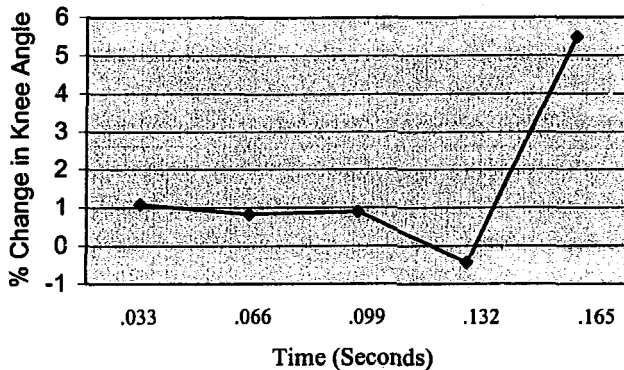


Figure 2. Average percent change in knee joint angle displacement over a 0.165 s period prior to take-off.

The average distance jumped was 99.03 ± 11.6 m. During the apparent stretch-shorten cycle movement, the average knee flexion was $-6.6 \pm 3.9^\circ$ and the average knee extension was $8.8 \pm 4.8^\circ$. Average knee angle flexion was represented as a negative angular change due to the decrease of the knee angle at the onset of the SSC movement. The average flexion/extension ratio was 0.85 ± 0.5 . The knee-joint extension velocity averaged 527.4 ± 45.9 deg/s (see Table 1). The quadratic relationship between jump distance and the amount of knee flexion is depicted in Figure 3.

Table 1. Average distance, average flexion, average extension, average flexion/extension ratio, and average radians per second.

Average Distance (m)	Average Flexion	Average Extension	Average Flex/Ext Ratio	Average Knee Ext. Velocity
99.03 ± 11.6	-6.6° ± 3.9°	8.8° ± 4.8°	0.85 ± 0.5	527.4° ± 45.9°

Values reported as Mean ± SE.

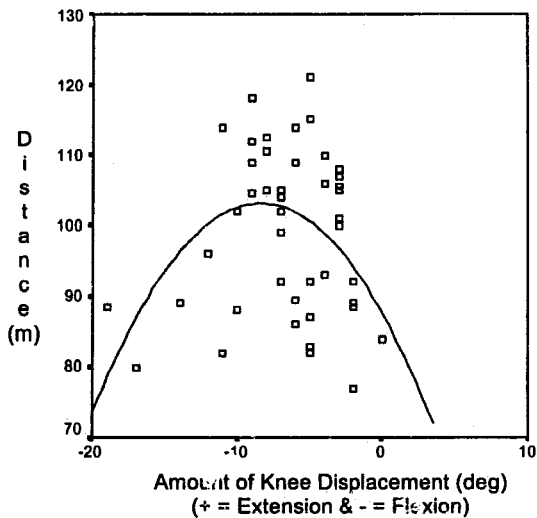


Figure 3. Quadratic relationship between amount of knee displacement (deg) and jump distance (m).

DISCUSSION

The purpose of the take-off is: (1) to give the jumper-ski system a maximum velocity, (2) to produce a favorable body position at the jump's edge, and (3) to provide an initial turning moment for the forward rotation of the body over the skis immediately after take-off (Campbell, 1980). This experiment adds another purpose to the take-off: to perform a stretch-shorten cycle.

The data show the existence of a stretch-shorten cycle (SSC) movement 0.08 s before the edge of the ski jump lasting approximately 66 ms. An elite ski jumper must utilize the SSC movement to increase their jump distance. It is important to recall the information in Figure 2. The data demonstrate there is a quadratic relationship between flexion of the knee joint and the jump distance. This demonstrates a relationship between optimal knee joint flexion and maximum jump distance. The mean flexion of the knee joint angle during the SSC movement was a - 6.6 °. Jumpers with a knee flexion between - 4 and - 9 ° during the SSC movement had the longest final jump distance results. This suggests that that when a jumper resists against and doesn't utilize the centrifugal force entering the take-off table to flex the knee joint, they may not be harnessing the full potential of the stretch-shorten cycle movement. Also, the jump distance may be hindered if the athlete flexes the knees too much. It is possible the proper knee joint flexion angle may create a build-up of elastic energy resulting in a more explosive knee extension velocity. This is all dependent on the jumper's ability to produce a quality take-off motion followed by a stable flight phase. Therefore, the stretch-shorten cycle may be an important factor in determining the length of the jump. It is important to

remember that several aspects must work together to produce a long jump distance. For example, a jumper may have a large knee extension velocity, proper form, and an ideal percentage of knee flexion, but if all of these components are not timed properly the jump distance will be negatively affected (Vaverka, 1987). Initiating the take-off motion 0.01 s early or late causes improper form during the flight phase and decreases the chances of producing a large jump distance (Schwameder, 1993).

Virmavirta and Komi (1993) observed that the peak knee-joint extension velocity occurs a few ms before passing the take-off edge. The average knee-joint extension velocity in the present study was $527.4 \pm 45.9^\circ$ or 9.2 ± 0.8 radians/s. This is lower than 12.0 radians/s that Virmavirta and Komi reported in 1993. This difference may be explained through the level of athletes observed. Virmavirta and Komi observed Olympic First team national and international competitors during the Olympics. The jumpers measured for the present study were comprised mainly of Second team national and international members, with a few First team members included.

The difference between knee-extension velocity from Virmavirta and Komi and the present study doesn't diminish the importance of the existence of the stretch-shorten cycle movement in ski jumping. Not only does the SSC movement exist, but also there may be an ideal amount of knee flexion to utilize the elastic energy in the SSC movement to produce a successful jump distance. Svantesson, Grimby, and Thomee (1994) found similar results in their data pertaining to the SSC movement. They found that an ideal degree of flexion exists to utilize the maximal muscle tension development and elastic energy storage. This study concluded that when an elite jumper utilized a proper stretch-

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APPENDIX A

REVIEW OF RELATED LITERATURE

REVIEW OF RELATED LITERATURE

Introduction

Biomechanical analysis of ski jumping dates back to 1927 when Strauman presented a detailed mechanical analysis based on wind-tunnel experiments. Ski jumping is a very complex skill involving several phases such as the inrun, take-off, flight, and preparation for landing. Each phase has importance to the length of the jump (Komi & Virnava, 1996). There are four phases in ski jumping: the approach run, the take-off, the flight, and the landing. The take-off phase is typically defined as the moment when the knee joint angle starts to increase entering the take-off table of the ski jump. The take-off has been identified as an important factor in achieving maximum distance (Vaverka, 1987). This is why previous investigations have focused on the knee angle entering into the take-off movement.

The take-off phase requires a high level of physical and technical performance. The athlete performs a movement that requires extension of the hip and knee joints to produce a negative aerodynamic effect (Antonio & Renato, 1987). The takeoff and flight phases of ski jumping have been the subject of a variety of studies (Komi & Virnava, 1996; Tveit & Pederson, 1981). The majority of the studies have been conducted on joint velocities and forces involved in the take-off phase of ski jumping (Hubbard, Hibbard, Yeadon, & Komor, 1989; Tveit & Pederson, 1981).

It is known that a stretch-shorten cycle is used in most athletic events (Wilson, Wood, & Elliott, 1991). However, there is a lack of literature concerning the possible use of a stretch-shorten movement in ski jumping.

FACTORS OF SKI JUMPING PERFORMANCE

Stretch-Shorten Cycle

The performance of an eccentric muscular action followed immediately by a concentric action is a stretch-shorten cycle (SSC) movement. This muscular pattern is apparent in running, jumping, throwing, hitting, and lifting activities (Wilson, et al., 1991). Research demonstrates that there are a few main reasons for the occurrence of SSC. These include neural augmentation, preload effect, storage and utilization of elastic energy, and two joint muscle energy transfer.

Neural Augmentation

Neural augmentation has been observed by Bosco, Tarkka, and Komi (1982). They confined the jumping movement to the ankle joint by ensuring that the subject's hip and knee joints were fixed. Subjects performed static jumps and countermovement jumps, and all subjects demonstrated significant neural augmentation due to prior stretch. The gastrocnemius EMG during running increased sharply from 35 to 45 ms after ground contact. This elevation in neural activity was two to three times as great as the activity recorded during a maximal voluntary isometric contraction (Bosco et al., 1982). They attributed the steep short latency increase in EMG to the spinal stretch-reflex. This was supported with the observation that, after partial blockage of type Ia afferent by ischemia, the short latency increase in EMG was markedly diminished during running. The

assumption that after 15 to 20 min of ischemia the type Ia afferent would be exclusively blocked was supported by the maximal voluntary isometric contraction was unaffected by ischemia (Dietz, Schmidtbleicher, & North, 1979). Burke, Hagbarth, and Lofstedt (1978) stated that during active lengthening contraction the muscle spindle responses were greater than during passive stretch, suggesting increased fusimotor outflow and reflex responses.

PreLoad Effect

Jones and Watt (1991), suggested that the preactivation is programmed and dispatched from the dorsal stretch reflex before landing. They stated that the correct timing and landing have been learned through previous experience. Avela, Santos, and Komi (1994) expanded on this concept and suggested that the control of landing is not solely regulated by the previous learning process, but is also influenced by fast adaptation of the vestibular apparatus. They also state that the electrical activity prior to the ground contact is the primary sensitive feature with respect to the various lead conditions. The second peak of EMG activity of lower limbs is related to the timing of landing in sudden falls in humans. This suggests that the vestibular apparatus is being involved in the initiation of this response (Greenwood & Hopkins, 1976).

Wilson (1991) demonstrated that the dominant view maintained by SSC researchers is that observed augmentation to concentric motion derived from prior stretch has neural origins. Komi (1987) demonstrated that the amount of preactivation increases with increasing running speed. It has been established that the use of the SSC augments the concentric phase of movement, resulting in an increase of movement, resulting in an

increase in work and power (Bosco & Komi, 1979). It has also been reported that the muscular activity recorded during the concentric phase of SSC activity is greater than that achieved during the same concentric movement performed without prior stretch (Bosco et al., 1982).

Further support of the SSC is also seen in data presented by Lockwood, Wood, and Roberts (1981) who compared the electromyography (EMG) of the rectus femoris of novice and elite jumpers. Both groups tended to produce the vast majority of their myoelectric activity in the concentric phase. Elite jumpers, however, produced a substantial portion of their muscular activity during the eccentric phase of the jumping movement. Therefore, the existence of neural augmentation to the SSC may occur primarily via an indirect route, that is, enhancing the storage of strain energy.

Storage and Utilization of Elastic Energy

The eccentric phase may allow the muscle time to develop tension in the tendon and fibers in the muscle itself. The series elastic components are in both the contractile elements and tendon (Shorten, 1987). Muscle must be considered as a potential source of significant storage of elastic energy due to the recent discovery of titin (Trinick & Tskhovrebova, 1999). Titin is a giant sarcomeric protein that runs from the Z-line to the M-line (Labeit & Kolmerer, 1995). The I-band segment of the molecule extends when slack sarcomeres are stretched or shortened, thereby functioning as a molecular spring that generates passive or restoring forces in skeletal and cardiac muscle (Higuchi, 1992). The elastic aspect of the segment can be determined from the sarcomeric binding sites of the sequences-specific anti-titin antibodies T12 and Ti-102 (Jin, 1995). Rief, Gautel,

Oosterhelt, Fernandez, and Gaub (1997) used a single-molecule atomic force microscopy (AFM) to investigate the mechanical properties of titin. They found that at large extensions the restoring force exhibited a sawtoothlike pattern, with a periodicity that varied between 25 and 28 nanometers. They also stated that the forces that were required to unfold the individual domains were from 150 to 300 piconewtons and depended on the pulling speed and upon relaxation, refolding of immunoglobulin domains were observed. This demonstrates elastic properties of the titin, the giant sarcomeric protein of striated muscle.

In 1995, Labeit and Kolmerer suggested that titin may act as two springs in series. They stated that the differential expressions of the springs provide a molecular explanation for the diversity of sarcomere length and resting tension in vertebrate striated muscles. Titin is likely to account for the intrinsic elasticity of vertebrate striated muscle myofibrils because degradation of titin by radiation or proteases or its removal by extraction results in a loss of passive tensions (Trinick & Tskhovrebova, 1999). Erickson (1997) found that the titin I-band segment accommodates physiological stretch by first straightening, but not unfolding, the immunoglobulin segments, and unfolding the in proline (P), glutamate (E), valine (V) and lysine (K) residues. This is also known as the PEVK domain. The unfolded PEVK may act more as a leash than a spring, exerting forces greater than 5 pN on near 80% of its maximal extension. These data suggest the significant role muscle may play in stored elastic energy utilization.

Svantesson, Grimby, and Thomee (1994) demonstrated that preceding muscle actions lead to greater concentric torque output between 90 and 99 ° plantar flexion.

However, the increase in the concentric action was significantly larger with eccentric than with isometric preceding actions, regardless of velocity. In this model their conclusion was that the main reason for large concentric torque values after a preceding muscle action is that time is sufficient for maximal muscle tension development; in addition, elastic energy is stored, particularly during the preceding eccentric action. In vertical jumping the use of elastic energy from the stretch-shorten movement accounts for approximately 12% of the total jumping height (Asmussen & Bonde-Petersen, 1974). This demonstrates that the stretch-shorten cycle movement may be an important factor in the takeoff phase of ski jumping.

Campbell (1980) collected data at the 1979 Pre-Olympic Games. His data concluded that the top finishers in the 70 m competition had a take-off phase with a higher forward rate of movement of the center of gravity over the base of support. This suggests that the highly skilled jumpers employed an early move forward into a more favorable position. Along with the more forward position of the center of gravity, "move in" may also provide a counter movement, which increases length and tension in the thigh muscles prior to extension, therefore increasing the strength and rate of contraction (Campbell, 1980).

Two Joint Muscle Energy Transfer

Take-off force is produced by joint movement (Virmavirta & Komi, 1989). In the take-off movement, properly timed joint and body segments are crucial, because reaction force is the result of the integrated kinetic parameters of each joint or segment. Those

kinetic parameters can be determined by the analysis of the jump action (Sasaki, Tsunoda, & Uchida, 1993).

It has been reported that the complex movement sequences involved in ski jumping were therefore more important in their contribution to optimal flight position than the ballistic properties of the ski jumper reduced to a single point model (Arndt, Bruggeman, Virravirta, & Komi, 1995). Two joints, the hip and the knee joint, produce most of the power, from initial action until take-off. The knee joint is the major energy and power producer in all jumpers (Sasaki, Tsunoda, Uchida, Hoshino, & Ono, 1996). The joint is a medium for transferring mechanical quantity, but the joint is not able to produce force or energy. Torque, energy, and power in the joints are produced within the upper segments and then transferred downward through the joint (Winter, 1990).

The purpose of the take-off is to increase the vertical lift and simultaneously maintain or even increase horizontal release velocities (Komi & Virravirta, 1996). In addition to high vertical and horizontal velocities, the purpose of the take-off movement is also to produce angular momentum. The somersault angle is used to describe the production of forward momentum during the ski jump take-off (Arndt, et al., 1995). Schwameder (1993) reported a significant correlation between the total distance of the jump and parameters that indicated a fast take-off movement: angle of projection, vertical take-off velocity of center of mass, and maximal knee angle velocity.

The relative angle for the knee joint at the initiation of the take-off phase for elite international subjects (90.18°) was less than demonstrated by the subjects from the U.S. (90.43°). This was directly related to the difference in position of the lower leg. The

angle of the lower leg for group International was 47.67° and the angle for the group U.S. was 50.15° . This represents a statistically significant difference (Sasaki, et al., 1993). The reduced angle of the lower leg and nearly identical positioning of the thigh indicated that the variability in the knee joint angle could be attributed to the positioning of the lower leg (Campbell, 1976). The knee-extension velocity is reportedly the highest correlating factor of all take-off parameters to the distance jumped (Arndt, et al., 1995). This suggests the importance of lower body joint angles in jump distance. However, little data are available concerning how these angles affect jump distance or how they differentially affect two joint energy transfer.

Summary

Research demonstrates that there are a few main reasons for the occurrence of SSC (Bosco et al., 1982). These include neural augmentation, preload effect, storage and utilization of elastic energy, and two joint muscle energy transfer. Each demonstrated a significant role in stored elastic energy utilization. It is known that a SSC is used in most athletic events (Wilson, et al., 1991). However, there is a lack of literature concerning the possible use of a stretch-shorten movement in ski jumping.

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