Efficacy of a 6-week Neuromuscular Training Program for Improving Postural Control in Figure Skaters

THESIS

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Abstract

The sport of ice figure skating has increasingly become more physically demanding in the past decade. It has been suggested that figure skaters should incorporate off-ice balance and ankle stability exercises into their normal training to potentially increase postural control. **PURPOSE:** 1) to determine the effectiveness of a 6-week neuromuscular training (NMT) program for improving postural control with respect to a variety of force plate measures, and 2) to determine the ability of force plate measures to predict figure skater skill level and competition experience. Our specific aim was to utilize force plate measurements to calculate mean velocity of the center of pressure (MVCOP) and time to stabilization of vertical ground reaction force (TTSz) for the purposes of 1) evaluating MVCOP and TTSz for a jump landing test before and after a 6-week NMT program, and 2) analyzing the correlations between subject characteristics and the dependent variables MVCOP and TTSz. To achieve our aim, we tested the following hypothesis: 1) compared with controls, MVCOP and TTSz for the SLS and SLL tests will ↓ following NMT, 2) at baseline, MVCOP and TTSz for the SLS and SLL tests will be inversely correlated with skater skill level and years of competition experience, and 3) compared with more experienced skaters, there will be a differential response to NMT such that less experienced skaters will improve to a greater extent.
METHODS: Twenty-six female freestyle figure skaters (age: 14.7±4.5 yr) with a wide range of competition experience (5.4±3.1 yr) were randomly assigned to a NMT group (n=14) or a control group (n=12). Training consisted of static and dynamic balance exercises on a variety of unstable platforms. Before and after a 6-week NMT intervention, MVCOP and TTSz were calculated from force plate measurements for two different 15 second trials (single leg stance, and a single leg landing from an 8 inch box). MVCOP was normalized to body mass to give relative MVCOP. RESULTS: Surprisingly, NMT did not differentially influence skaters of different levels of skill or experience. Furthermore, our results indicate no significant baseline correlation between years of competition experience, skating level, and hours of weekly on-ice practice with the dependent variables MVCOP and TTSz. Relative MVCOP for the SLS test did not change for the training group from baseline (1.94±1.88 mm/s/kg) to post-intervention (1.88±0.88 mm/s/kg), but did decrease significantly from baseline (1.56±0.77 mm/s/kg) to post-intervention (1.42±0.70 mm/s/kg) for the control group (p < 0.05). Relative MVCOP for the SLL test did not change for the training or control groups from baseline (2.53±1.17 mm/s/kg, 2.27±0.93 mm/s/kg, respectively) to post-intervention (2.50±1.02 mm/s/kg, 2.16±0.98 mm/s/kg, respectively). TTSz decreased significantly for the training and control groups from baseline (3941±57 ms, 3892±72 ms, respectively) to post-intervention (3854±61 ms, 3784±94 ms, respectively). However, there were no significant differences between the training and control groups at baseline or following the intervention for any test. CONCLUSIONS: The 6-week NMT program offered in this study did not improve postural control with respect to MVCOP during the SLS and
SLL tests. It is inconclusive what contribution the NMT program may have made to the observed improvement in TTSz as both the training and control groups improved to the same extent. In all likelihood, it was the suspected increase in on-ice training time (for skaters from both groups) during the summer intervention period, rather than NMT, that influenced TTSz. Future research should examine the effects of NMT on success in competition and incidence of injury.
Dedicated to my wife, Karyn, and my daughter, Kayleigh

They are my inspiration
Acknowledgments

I thank Dr. Steven Devor for mentoring me through this study from conception to completion.

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Publications


Fields of Study

Major Field: Education
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Chapter 1: Introduction

The sport of ice figure skating in the United States has experienced a tremendous increase in participation in the last two decades. United States Figure Skating membership has grown from 100,000 members in 1992 to 178,500 members in 2007, with 74% of the current membership represented by female skaters [1]. Coincident with membership growth were two major structural changes, which have dramatically increased the physical demands placed on the athletes. First, in 1990, the elimination of school figures, circular patterns which skaters trace on the ice to demonstrate skill in placing clean turns evenly on round circles [2], permitted skaters to spend more time practicing free skating elements (e.g., jumps and spins) [3]. Second, in 2004, in an attempt to make judging less subjective, the 6.0 scoring system was reevaluated and ultimately replaced with the International Judging System [4]. The new scoring system was designed to award points for each specific element rather than a single mark to represent a collection of elements. The scoring system change encourages skaters to maximize the difficulty of each element in a routine including the strategic placement of jumps in the second half of a routine for bonus points.

Possibly as a result of the increased physical demands, overuse injuries (primarily in the lower back and lower extremity) are more prevalent now than ever before [5-10]. It has been shown that preventive training, involving the improvement of ankle and knee
stability, may be beneficial to all youth athletes participating in sports requiring pivoting and landing [11]. Studies specific to figure skaters have concluded that off-ice conditioning programs emphasizing balance and ankle stability should be incorporated into the normal training programs of skaters [3, 8, 12].

To our knowledge only two studies have investigated postural control in figure skaters [13-14]. Both agree that figure skating is a sport that significantly challenges the three sensory components of postural control (visual, vestibular, and somatosensory systems). Riva et al. [14] found that ice dancers demonstrated greater proprioceptive abilities than freestyle skaters when balancing in an eyes closed condition. They concluded that freestyle skaters specifically would likely benefit from improving their proprioceptive strategies to enhance the quality of their skating, but offered no training suggestions to achieve the goal.

In 2004, Kovacs et al. investigated the effect of a four week neuromuscular training (NMT) program on the postural control of figure skaters compared to skaters participating in basic strength and flexibility training [13]. Skaters in the NMT group performed one and two leg balance exercises of varying degrees of difficulty (eyes open or closed, stable and unstable surfaces). Skaters in the basic conditioning group performed running, push-ups, abdominal crunches, wall-sit exercises, and a variety of stretches. Postural control was measured indirectly via center of pressure (COP) displacements on a force plate during five different balance tasks (single limb balance with eyes open and closed, single limb balance with skate on and eyes open, landing backward from a platform with eyes open and closed). For all tests, 15 seconds of force
plate output was collected and averaged for final analysis. The main outcome measure was the total path length of the COP displacements for the 15 second trial durations. Measurements were taken before and following training. They found a significant difference in the percent change in postural control between the two groups. However, NMT only improved postural control with respect to the two most challenging tasks, single limb balance with skate on and eyes open, and landing backward from a platform with eyes closed. It was suggested that the intermediate to senior level figure skaters in their study may have had such a relatively high baseline level of postural control that the single limb stance test and the landing test, both completed with eyes open, were not challenging enough to employ the possible proprioceptive enhancement resulting from the NMT.

Due to the extensive on-ice training demand on figure skaters, off-ice programs need to efficiently and effectively improve performance and reduce the risk of setbacks resulting from injury. It is arguable that the training program utilized by Kovacs et al. did not elicit a measurable functional change in postural control (e.g., a jump landing with eyes closed). We argued that a program designed to improve postural control is only beneficial if there are improvements in postural control during tasks that represent the functional demands of the sport (e.g., landing test with eyes open). While path length of COP displacements is a fine measure of postural control for a variety of subject populations, time to stabilization of the vertical ground reaction force (TTSz) is likely more functionally relevant to figure skaters. Figure skaters are expected to perform multi-revolution jumps in combination (two consecutive jumps without a change of foot
in between) [2]. The latency between the landing of the first jump and the takeoff of the second jump is typically less than one second. Therefore, it is of particular interest what happens in the first few seconds of a jump landing, rather than 15 seconds of static balance. The purposes of the present study were (1) to determine the ability of force plate measures to predict figure skater skill level and competition experience, and (2) to determine the effectiveness of a 6-week NMT program for improving postural control with respect to a variety of force plate measures. Our main outcome measure was TTSz for a single leg landing (SLL) test with eyes open.
Chapter 2: Review of Literature

Postural Control Defined

Postural control may take on many different meanings depending on context. For the purpose of the present study postural control represented the ability to maintain equilibrium in a gravitational field by keeping the center of body mass (COM) over its base of support (BOS) [15]. In terms of standing, COM is the point at which the vector of total body mass passes [16], and the BOS is the area of contact between the foot and support surface [17]. However, a human foot is not a rigid uniform structure and should not be thought of as such. Therefore, the true BOS is not simply foot area; it also must include joint stiffness and skeletal muscle strength in the foot.

There are two major components of postural control 1) a feedback component which reacts to an external disturbance of balance 2) a feedforward component which anticipates a self-generated disturbance and activates supporting muscles prior to prime mover activation [15, 18-19]. An external disturbance would include unstable support surfaces, misleading audio or visual cues, and physical contact. Self-generated disturbances include the volitional movement of body parts resulting in a shifting of the COM. For example, if a subject were to reach to pick up an object off a counter top their COM would be shifted in an anterior direction. In anticipation of the forthcoming movement the appropriate behavior is to compensate by shifting the COM in the
posterior direction, thereby maintaining the COM over the BOS. The degree of anticipatory compensation depends on the perception of the magnitude of COM displacement, which is dependent on experience.

Postural Strategies

A postural strategy refers to the type of stereotypical movement that is employed to compensate for disturbance of balance. While deviations of the COM remain within the BOS an ankle or hip strategy may be employed in response to balance perturbations [15, 20]. However, once the COM deviates beyond its BOS a step must be taken (stepping strategy). The ankle strategy is the most common postural strategy and involves distal to proximal leg muscle activation resulting in movement of the COM in the sagittal plane [15, 21]. The hip strategy is generally recruited in response to large and fast disturbances or a relatively small base of support and involves proximal to distal trunk and thigh muscle activation [15, 21]. In 1986, Horak and Nashner reported the response latencies of the ankle and hip strategies to be 100-125 ms and 105-145 ms respectively [21]. The selection of two distinct postural strategies (ankle and hip) is influenced by prior experiences and current sensory information suggesting that it may be able to be trained [21]. While the selection process may be adaptable, Horak et al. suggested that it is still automatic [22].

Postural Control Sensory Systems

The somatosensory, vestibular, and visual systems are always actively delivering sensory information that is essential for postural control [15, 23-25]. Much of the time, signals being simultaneously transmitted from these sensory systems carry conflicting
information about orientation, and higher brain centers (primarily the cerebellum) must determine which signals portray the most accurate information given the collective stimuli [26-27]. Therefore, depending on the situation the information from some systems hold more weight than others. However, these systems are also somewhat redundant, so the elimination of one or more of these systems does not necessarily greatly influence postural control under normal circumstances [22, 24].

Horak et al. studied the effects of vestibular loss and somatosensory loss on postural control [22]. Subjects with vestibular loss were recruited, while somatosensory loss was induced by ischemic hypoxia at the ankle. In the first experiment, subjects from the control, vestibular loss, and somatosensory loss groups were asked to maintain standing bipedal equilibrium on movable forceplates. The forceplates were randomly displaced in the anterior-posterior directions. Subject sway and EMG activity in response to these displacements was monitored and recorded. Compared with controls, subjects with either sensory deficit were unable to automatically respond to the disturbances with the appropriate postural control strategy. Furthermore, even when the subjects were asked to voluntarily select the appropriate strategy, those with sensory loss were unable to do so. It was concluded that the automatic strategy selection process is dependent on reliable information from all three sensory systems.

In the second experiment, subjects from the control, vestibular loss, and somatosensory loss groups were asked to maintain standing bipedal equilibrium during variable visual and surface conditions. Normal subjects and those with somatosensory loss were able to perform equally under all conditions. Likewise, subjects with vestibular
loss were able to perform equally to normal subjects as long as either visual or somatosensory information was reliable. However, when both the surface and vision were altered simultaneously vestibular deficient subjects went into almost immediate freefall. Horak et al. concluded that under the normal condition of quiet stance, vestibular information is not essential as long other reliable sensory information is available.

Magnusson and Johansson investigated the significance of the vestibular system via galvanic stimulation of the vestibular nerve [28]. By disrupting the vestibular feedback in otherwise normal subjects they were able to induce anterior-posterior sway, indicated by movement of the center of pressure (COP) calculated from force plate data. Somewhat contradicting the findings of Horak et al. [22], even with reliable visual and somatosensory information the vestibular system was contributing to the maintenance of balance during quiet stance. It is possible that the different outcomes are a result of the experimental methods. Horak et al. utilized subjects with clinical vestibular loss, while Magnusson and Johansson induced vestibular deficiencies with galvanic stimulation. Peterka and Benolken were able to qualify the relative contribution of the vestibular system under varying conditions with a customary set of experiments [25]. Two subject groups, consisting of normal healthy subjects and subjects with vestibular loss, were asked to maintain standing equilibrium under the condition of visual surround rotations, with and without accurate somatosensory feedback. At low levels of visually induced sway there were no differences between groups with respect to sway amplitude or frequency. However, at higher levels of visually induced sway a saturation effect was
achieved in the normal group, but not in subjects with vestibular loss. Therefore, supporting the results of Horak et al. [22], it was suggested that the threshold for a vestibular response is high relative to visual and somatosensory systems implying that vestibular information does not contribute significantly to balance during quiet stance under normal conditions.

According to Nashner and Bertholz, there is a rapid and slow component to the visual influences on postural control [26]. Their unique experimental apparatus included a movable support surface and a movable visual enclosure (a stirafoam box). Subjects were asked to stand relaxed under three different conditions. In the first experiment, the support was translated backward causing anterior sway of the subject while the visual field remained fixed. Under this condition the subjects had accurate visual feedback with respect to their orientation and sway acceleration. In the second experiment, the support was translated backward causing anterior sway of the subject, but this time the visual field moved forward to the same extent as the head of the subjects. Under this condition the subjects were visually unaware of sway acceleration and magnitude. In the third experiment, the support was translated backward causing anterior sway of the subject, but this time the visual field moved backward to the same extent as the support. Under this condition the subjects overestimated their sway acceleration and magnitude. Each experiment was repeated five times for every subject.

Importantly, there was a decrease in sway amplitude from the first to the fifth trial under all conditions, thereby indicating a rapid adaption and a reweighting of postural control sensory influences. As the trials progressed subjects became less reliant on the
inappropriate visual stimuli in favor of somatosensory and vestibular feedback. The visual field moving in the direction of sway produced the greatest sway magnitude and latency. The visual field moving against the direction of sway produced the smallest sway magnitude and latency.

Ledin and Odkvist discovered that vision contributed to postural control in an unexpected manor [19]. In their experiments normal healthy subjects attempted to maintain standing bipedal equilibrium on a movable force plate under two different visual conditions (eyes open and eyes closed). The plate was then displaced forward and backward at amplitudes ranging from 13 to 127 mm. Their two variables of interest were the magnitude of the COP response to the support disturbance at each amplitude, and the latency from support disturbance to muscular correction. As expected, there was an increasing linear relationship between the amplitude of support displacement and the magnitude of the COP response. At greater degrees of displacement this relationship flattened out indicating a saturation point. The latencies, though, were surprising. While the visual condition had no significant influence on the magnitude of the COP response, it was in the eyes closed condition that the response time was the fastest. It was suggested that the subjects felt more comfortable in the eyes open condition and therefore did not respond as abruptly. This finding was in agreement with Magnusson and Johansson [24].

Postural Control Motor Response

After sensory information about a perturbation to balance is received from the aforementioned systems, a timely and coordinated motor response must occur to maintain
postural control. There are three levels of motor responses to disturbance of balance. The quickest of these is the myotatic stretch reflex with a response latency of about 40 to 50 ms [26]. As with all reflexes, this response cannot be modified. In 1997, Nashner et al. proposed that the earliest response to provide functional stability to a standing individual was an automatic postural movement with a latency of approximately 100 ms [17, 29]. While not under voluntary control, the automatic responses were thought to be adaptable and modifiable based on experience. Voluntary responses are the slowest of the motor circuits with a minimum latency of 150 ms [17].

*Postural Control Assessment Techniques*

Postural control assessments aim to measure deviations in the COM in response to a variety of stimuli or the removal of various sensory systems. However, COM is difficult to measure, so many investigators estimate its position using posturography [30]. Posturography directly measures changes in the COP on a force plate [31]. During static balance tests on a level and stable support surface the body is assumed to behave as a rigid structure rotating only at the ankle in the sagittal and frontal planes like an inverted pendulum [22-23, 30, 32-34]. Hasan et al. found the frequency and amplitude of COM and COP measurements to be highly correlated, and therefore supported the use of posturography for assessing standing balance [32].

Force plates measure the three orthogonal components of force (vertical and two horizontal forces) and their respective moments [35]. These components are collectively used to calculate COP in the sagittal and frontal planes. It has been common practice to sample at rates anywhere from 20 to 1000 Hz [19, 22, 35-39]. Data in most cases is then
downsampled or filtered to remove noise [30, 32, 36, 39-42]. Few have justified their use of a particular sampling rate. Two studies have suggested that analysis of data downsampled to 10 Hz is the most physiologically meaningful [36-37, 43-44]. Their rational was that automatic learned responses occur with a latency of about 100 ms (≈10 Hz) with voluntary responses requiring even more time, about 150 ms (≈6.7 Hz). Therefore, any data at frequencies greater than 10 Hz should be considered noise. If retained for analysis it would dilute the meaningful data. However, a more common objective practice is to perform a spectral analysis to identify dominant frequencies in the data. Then, according to the Nyquist Theorem, the highest frequency identified in spectral analysis is multiplied by 10. Finally, the raw data would be filtered or downsampled to the resulting frequency to prevent oversampling and eliminate noise.

At any instant the COP is a single point with the coordinates (X_{net}, Y_{net}). Once the COP coordinates are determined a variety of variables may be calculated which correspond to different aspects of postural control. The most common COP metrics include path length (frontal, sagittal, and global), mean velocity (frontal, sagittal, and global), amplitude or range (frontal and sagittal), area, and sway root mean squared [15-16, 34, 37, 40-41, 45-47]. Many of these metrics are highly correlated and therefore contribute similar information [35, 41]. According to Kim et al. path length is affected less by weight and height than is root mean squared or range values [35]. Mean velocity of the COP (total path length divided by total time) is slightly more useful as it normalizes the data and permits comparisons between trials of different durations. The
mean velocity is calculated as follows (adapted from Cornilleau-Peres and Kim et al. [35, 48]):

\[
V = \frac{1}{T} \sum_{n=1}^{N} \sqrt{[X_{net}(n) - X_{net}(n-1)]^2 + [Y_{net}(n) - Y_{net}(n-1)]^2}
\]

where \(V\) is the global mean velocity of the COP, \(N\) is the total number of samples, and \(T\) is the total trial duration in seconds. Ross et al. [39] observed a decrease in MVCOP for single leg stance following 6-weeks of coordination training in subjects with functional ankle instability (FAI).

While the COP metrics typically examine mean COP displacements over an extended trial duration of anywhere from 10 to 60 seconds, time to stabilization (TTS) identifies the latency between the initial contact with a force plate from jump landing and the point at which the subject achieves relatively stable ground reaction forces (GRF). Previous studies have objectively determined TTS as the point where the sequential average of the GRF remains within ±0.25 standard deviations of the overall mean [49-51]. Typically TTS has been measured upon landing from a specific jump-landing task [52]. Subjects would be asked to jump a distance of 70 cm at 50% of their maximum vertical jump height and land in the center of a force plate on one leg. They would then be instructed to stabilize as quickly as possible and remain in a single leg stance minimizing movement until instructed to stop 20 seconds later. Different sampling frequencies have been used for collection and analysis of TTS, but Ross et al. argued that based on spectral analysis a minimum of 60 Hz is sufficient. However, they suggested that jumping from a box, rather than the previously described jump-landing task, may be
more appropriate as it would control for acceleration and likely limit variation between tests and between subjects [52].

While TTS may have a wide range of application, it is most commonly used to assess lower limb injuries [50-51]. Colby et al. [50] found TTS of the vertical GRF (TTSz) during a step down test was able to discriminate between limbs with deficient or reconstructed anterior cruciate ligaments (ACL) and uninjured limbs. Limbs with an injured ACL had significantly greater TTSz. It was suggested that ACL injuries may reduce proprioceptive feedback from the joint leading to inhibited stabilization times. TTS has also been used to discriminate between functionally stable and unstable ankles [51]. It was observed that there was more variation in the GRF during static balance for functionally unstable ankles. For that reason they recommended the use normative values to calculate TTS for these individuals.

*Postural Control in Figure Skaters*

Possibly as a result of the increased physical demands, overuse injuries (primarily in the lower back and lower extremity) are more prevalent now than ever before [5-10]. It has been shown that preventive training, involving the improvement of ankle and knee stability, may be beneficial to all youth athletes participating in sports requiring pivoting and landing [11]. Studies specific to figure skaters have concluded that off-ice conditioning programs emphasizing balance and ankle stability should be incorporated into the normal training programs of skaters [3, 8, 12].

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Due to the extensive on-ice training demand on figure skaters, off-ice programs need to efficiently and effectively improve performance and reduce the risk of setbacks resulting from injury. It is arguable that the training program utilized by Kovacs et al. did not elicit a measurable functional change in postural control (e.g., a jump landing with eyes closed). We argued that a program designed to improve postural control is only beneficial if there are improvements in postural control during tasks that represent the functional demands of the sport (e.g., landing test with eyes open). While path length of COP displacements is a fine measure of postural control for a variety of subject populations, time to stabilization of the vertical ground reaction force (TTSz) is likely more functionally relevant to figure skaters. Figure skaters are expected to perform multi-revolution jumps in combination (two consecutive jumps without a change of foot in between) [2]. The latency between the landing of the first jump and the takeoff of the second jump is typically less than one second. Therefore, it is of particular interest what happens in the first few seconds of a jump landing, rather than 15 seconds of static balance. The purposes of the present study were (1) to determine the ability of force plate measures to predict figure skater skill level and competition experience, and (2) to determine the effectiveness of a 6-week NMT program for improving postural control
with respect to a variety of force plate measures. Our main outcome measure was TTSz for a single leg landing (SLL) test with eyes open.
Chapter 3: Methods

Subjects

Participants of this study were recruited from local Chiller Ice Rinks in Columbus, OH. Eligible participants were female figure skaters 10 to 28 years of age with at least one year of competition experience and an average of two hours of on-ice practice per week. Skaters were excluded from this study if they recently missed practice due to injury, if they had any physical or physiological deficiencies affecting balance (e.g. scoliosis, ear infection), or if they had a known pregnancy. Informed written consent was obtained from all subjects before participation in this study. The Ohio State University Institutional Review Board granted approval of this study. In all, 29 subjects volunteered for this study and completed the baseline postural control assessment. Three subjects dropped out, one due to a skating injury, and two others due to scheduling conflicts (data from those subjects were not included in the results). All 26 subjects that completed this study were singles freestyle skaters.

Table 3.1 Descriptive Characteristics of subjects (Mean ± SD). N=26.

<table>
<thead>
<tr>
<th></th>
<th>Control (n=12)</th>
<th>Training (n=14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>15.5 ± 5.3</td>
<td>14.1 ± 3.9</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>157.7 ± 10.4</td>
<td>154.2 ± 9.0</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>51.9 ± 11.5</td>
<td>47.2 ± 10.5</td>
</tr>
<tr>
<td>Competition Experience (y)</td>
<td>5.3 ± 4.0</td>
<td>5.5 ± 2.3</td>
</tr>
<tr>
<td>Practice Time/Week (hr)</td>
<td>4.6 ± 2.5</td>
<td>6.8 ± 4.8</td>
</tr>
</tbody>
</table>
Study Design

We employed a randomized control design for this study. All interested subjects meeting the inclusion criteria were given a baseline postural control assessment at The Ohio State University (OSU) Sports Biomechanics Laboratory. After completion of all baseline measurements subjects were randomly assigned to one of two groups, Neuromuscular Training (NMT), or Control. The subjects were block randomized stratified by age and weight. Subjects assigned to the NMT group then selected three of 13 weekly classes to attend for the following six consecutive weeks. Control subjects were asked to continue their normal training for the duration of the study. Following the 6-week intervention all subjects returned to the OSU Sport Biomechanics Laboratory for a follow-up postural control assessment.
In Instruments and Data Analysis, to assess the postural control of each subject we utilized a Bertec 4060-10 force plate (Bertec Corporation, Columbus, OH). The plate was mounted flush with the laboratory floor and had the dimensions 40 cm X 60 cm. The force plate had the capability of measuring six components: three orthogonal forces and the moments about each axis. From those components we were able to calculate center of pressure (COP) and ground reaction force (GRF), indirect measurements of postural sway in both the sagittal and frontal planes. The most common COP metrics include path length (frontal, sagittal, and global), mean velocity (frontal, sagittal, and global), amplitude or range (frontal and sagittal), area, and sway root mean squared [15-16, 34, 37, 39-41, 45-47].

Figure 3.1 Outline of balance testing and training.
Many of these metrics are highly correlated and therefore contribute similar information [35, 41]. The most common GRF metrics include standard deviation of the vertical GRF and time to stabilization of GRF (TTS) [49-51].

Data was collected at a sampling rate of 1000 Hz utilizing Vicon Nexus software (Oxford Metrics, Oxford, UK). All data processing and analyses were performed with custom made Matlab programs (Matlab R2009a, Natick, MA, USA). We elected not to filter the data because of the use of nonlinear analyses. Spectral analysis identified 10 Hz as the highest dominant frequency. Applying the Nyquist Theorem, we multiplied that frequency by 10 giving us a sampling rate of 100 Hz. We then downsampled to 100 Hz by selecting every 10th data point [36-37, 43-44]. Finally, we performed an additional spectral analysis on the downsampled data to confirm our methods.

We elected to study the Mean Velocity of the COP (MVCOP) and time to stabilization of the vertical ground reaction force (TTSz). MVCOP has been shown to be inversely correlated with postural control and is affected less by weight and height than is root mean squared or range values [35, 39]. MVCOP (total path length divided by total time) is slightly more useful than the total path length measure utilized by Kovacs et al. as it normalizes the data and permits comparisons between trials of different durations [35]. MVCOP was calculated as follows (adapted from Cornilleau-Peres and Kim et al.) [35, 48]:

\[ V = \frac{1}{T} \sum_{n=1}^{N} \sqrt{\left[ X_{net} (n) - X_{net} (n-1) \right]^2 + \left[ Y_{net} (n) - Y_{net} (n-1) \right]^2} \]
where $V$ is the global mean velocity of the COP in mm/sec, $N$ is the total number of samples, and $T$ is the total trial duration in seconds.

We calculated TTSz as described by Colby et al. [50]. Briefly, an average of the vertical ground reaction forces (GRFz) for the entire trial duration (14 seconds) was taken. TTSz was identified as the point where the sequential average of the GRFz remained within $\pm 0.25$ standard deviations of the overall mean (Figure 3.2).
Figure 3.2 This is an example of how Time to Stabilization of the vertical ground reaction forces was calculated for a single leg landing test with a 14 second trial duration. The solid line of best fit represents the sequential average of the vertical ground reaction forces (GRFz). The two horizontal dotted lines represent ±0.25 standard deviations from the overall mean. The vertical dashed line represents the point where the sequential average of the GRFz entered and remained within ±0.25 standard deviations of the overall mean.

Balance Testing

Participants arrived at the testing facility the day of their baseline postural control measurements and were immediately given appropriate consent documentation to read and sign (minors, accompanied by a legal guardian, were given assent forms and parental permission forms, adults were given consent forms). Once we had obtained consent, the
subjects were asked to remove their shoes for weight and height measurements. Next, the subjects were introduced to the testing room for familiarization. During this familiarization period the investigator explained the function of the force plates embedded in the laboratory floor and described the general testing format.

Subjects were assigned two separate eyes open balance tasks to be completed on the force plate. The first test (Figure 3.3 A) was a single leg stance (SLS). The investigator read standardized instructions to the subjects and demonstrated the exercise. Once the subjects had demonstrated the balance position properly (arms crossed over their chest, supporting knee slightly bent, and free foot lifted off the floor) they were then positioned on the force plate. The subjects were asked to place the second toe of their landing foot on the anteroposterior midline of the plate with their medial malleolus positioned at the mediolateral midline. They were then instructed to maintain focus on the doorway centered in front of them and to assume the SLS balance position. Data sampling was manually initiated by remote when verbally cued by the subjects, indicating they were stable. Subjects were asked to remain as motionless as possible until the investigator indicated the 15 seconds of data acquisition were complete. Any test in which the subjects were unable to maintain unassisted balance for the full 15 seconds resulted in a failed test. The test was repeated with a 30 second rest between each trial until they had completed three successful trials, but no more than six total attempts. An average of the three successful trials was taken for data analysis.

The second test (Figure 3.3 B) was a single leg landing (SLL) from a box. Again the investigator read standardized instructions to the subjects and demonstrated the
exercise. The subjects were asked to stand on a 20 cm high platform positioned 10 cm in front of the force plate. Standing with their heels at the edge of the platform they were instructed to jump backwards from two feet landing on the force plate on one foot in a figure skater landing position (arms extended to their sides, chest upright, free leg extended behind them, and supporting knee bent to the angle of their choosing). Unlike the SLS test, position on the plate was unimportant so long as no part of their foot was in contact with the floor surrounding the plate. Each subject was asked to practice the exercise three times to diminish any learning effect that might occur (during the practices they only held the landing position for five seconds to minimize fatigue). Following the three practice attempts the subjects were asked to assume the starting position on the block. They were then asked to jump whenever they were ready. Data sampling was manually initiated by remote at the initiation of the jump (two seconds of data was recorded prior to the manual trigger for each SLL trial). Upon landing, subjects were asked to remain as motionless as possible until the investigator indicated the 17 seconds of data acquisition were complete. Any test in which the subjects were unable to maintain unassisted balance, or lost contact with the plate after initial contact, for the full 17 seconds resulted in a failed test. The test was repeated with a 30 second rest between each trial until they had completed three successful trials, but no more than six total attempts. An average of the three successful trials was taken for data analysis. The same testing protocol was used for post intervention assessments.
Figure 3.3 Balance tests. A, single leg stance with arms crossed over chest and eyes open. B, single leg landing from 8 inch box.

Neuromuscular Training

The neuromuscular training (NMT) program utilized in the present study was adopted and modified from that used by Kovacs et. al. [13]. Subjects assigned to NMT were asked to complete eighteen 30 minute group classes over a period of six consecutive weeks (three classes per week). The class was organized in a circuit fashion and consisted of seven different exercise stations and three rest stations. This permitted a maximum of 10 skaters per class.

Five different trained instructors independently taught the 13 classes we offered weekly (at three different training facilities) to accommodate the varied schedules of our subjects. Attendance was recorded for the purpose of monitoring training compliance. Each exercise apparatus was aligned such that subjects were unable to see their reflection
in a mirror or window (Figure 3.4 A). While the exercises were always arranged in the same order for all classes, at the beginning of each class skaters were permitted to choose their own starting position. All exercises were performed barefoot. For all exercises the instructor would verbally indicate the beginning of a new repetition. At that time all skaters would assume their respective balance positions. Each repetition was held for 20 seconds (skaters were instructed return to their balance position as quickly as possible should they falter). At the end of each repetition all skaters were instructed to rest for 15 seconds before repeating the exercise on the opposite leg. This would continue at each station until they had completed three repetitions on each leg (for two-leg exercises the same exercise was repeated six times). After every three minute segment skaters were instructed to change stations.
Figure 3.4 Neuromuscular training exercises. A, exercise and rest station arrangement (white signs on the floor represent three minute rest stations). B, single leg stance on floor. C, landing position on rocker board moving in the anterior-posterior plane. D, two leg stance on wobble board moving in the medial-lateral plane. E, two leg stance on Disco Sit. F, single leg stance on Disco Sit. G, landing position on Disco Sit. H, two leg jump to single leg landing on mini trampoline.

Statistical Analyses

Pearson correlations were used to examine the relationship between subject characteristics (Age, Height, Weight, Years of competition experience, and Hours of
weekly on-ice practice) and the dependent variables (MVCOP and TTSz). Before performing the statistical analyses, we normalized MVCOP values, for each subject, to body mass. Statistical analyses were performed by STATA (Version 11, 2009; StataCorp LP, College Station, Texas) for relative MVCOP and TTSz. Between group differences were determined with a two-tailed two-sample t-test. Baseline to post-intervention differences were determined with paired t-tests. The significance level was set a priori at 0.05.
Chapter 4: Results

Training Adherence

Training logs were kept for all skaters receiving the intervention. On average, skaters attended 88.1±7.8% of their scheduled weekly training sessions (about 16 of 18 sessions). No skater missed more than two consecutive sessions or more than five total sessions.

Single Leg Stance Test

Body mass was found to be significantly correlated with MVCOP for both groups and both tests at baseline and post-intervention. To account for this relationship in the data analysis we normalized MVCOP to body mass giving us relative MVCOP with the units (mm/s/kg). Figure 3.5 shows the relative MVCOP during the SLS test for the NMT and control groups before and after the 6-week intervention. Relative MVCOP did not change for the training group from baseline (1.94±1.88 mm/s/kg) to post- intervention (1.88±0.88 mm/s/kg). Relative MVCOP did decrease significantly from baseline (1.56±0.77 mm/s/kg) to post-intervention (1.42±0.70 mm/s/kg) for the control group (p < 0.05). However, there were no significant differences between the training and control groups at baseline or following the intervention.
Figure 4.1 Relative mean velocity of the center of pressure (MVCOP) for the single leg stance test at baseline and following a 6-week neuromuscular training intervention. The training group and control group are shown in black and grey respectively. Error bars represent one standard deviation from the mean. * indicates a significant within group change from baseline to post-intervention (p<0.05).

Single Leg Landing Test

Body mass was found to be significantly correlated with MVCOP for both groups and both tests at baseline and post-intervention. To account for this relationship in the data analysis we normalized MVCOP to body mass giving us relative MVCOP with the units (mm/s/kg). Figure 3.6 shows the relative MVCOP during the SLL test for the NMT and control groups before and after the 6-week intervention. Relative MVCOP did not change for the training or control groups from baseline (2.53±1.17 mm/s/kg, 2.27±0.93
mm/s/kg, respectively) to post-intervention (2.50±1.02 mm/s/kg, 2.16±0.98 mm/s/kg, respectively). There were no significant differences between the training and control groups at baseline or following the intervention.

![Single Leg Landing Test](image)

**Figure 4.2** Relative mean velocity of the center of pressure (MVCOP) for the single leg landing test at baseline and following a 6-week neuromuscular training intervention. The training group and control group are shown in black and grey respectively. Error bars represent one standard deviation from the mean.

**Time to Stabilization**

Unlike MVCOP, time to stabilization of the vertical ground reaction force (TTSz) was not significantly correlated with any subject characteristics, including body mass.
Furthermore, two-tailed *two-sample t-tests* revealed no baseline differences in TTSz between the lowest third and the highest third of all skaters with respect to years of competition experience, skating level, and hours of weekly on-ice practice. Therefore, it was not necessary to normalize TTSz data. Figure 3.7 shows the TTSz during the SLL test for the NMT and control groups before and after the 6-week intervention. TTSz decreased significantly for the training and control groups from baseline (3941±57 ms, 3892±72 ms, respectively) to post-intervention (3854±61 ms, 3784±94 ms, respectively). However, there were no significant differences between the training and control groups at baseline or following the intervention.
Figure 4.3 Time to Stabilization of the vertical ground reaction force (TTSz) for the single leg landing test at baseline and following a 6-week neuromuscular training intervention. The training group and control group are shown in black and grey respectively. Error bars represent one standard deviation from the mean. * indicates a significant within group change from baseline to post-intervention (p<0.05).
Chapter 5: Discussion

Our results support the findings of Kovacs et al. [13] that NMT is not a sufficient stimulus to elicit an improvement in COP path length with respect to SLS and SLL tests with eyes open. Only the control group improved MVCOP for the SLS test at follow-up, and no improvement in MVCOP was observed in either group for the SLL test. This was true even though the present NMT program was two weeks longer with longer session durations than that offered by Kovacs et al (30 vs. 20-25 minutes). They suggested that the intermediate to senior level figure skaters in their study may have had such a relatively high baseline level of postural control that the SLS test and the SLL, both completed with eyes open, were not challenging enough to employ the possible proprioceptive enhancement resulting from the NMT.

To address the idea that baseline skating experience may have had an impact on the effectiveness of NMT we recruited skaters with less competition experience than those utilized by Kovacs et al. (5.5±2.3 vs. 12±4 years). Additionally, we recruited a much wider range of skating levels (beginner to senior vs. intermediate to senior). Surprisingly, NMT did not differentially influence skaters of different levels of skill or experience. Furthermore, our results indicate no significant baseline correlation between years of competition experience, skating level, and hours of weekly on-ice practice with the dependent variables MVCOP and TTSz.
The observation that NMT did not differentially influence skaters of different levels of skill or experience may suggest that the NMT program did not sufficiently challenge even the lowest level skaters, or the intervention duration was too brief. Based on feedback from class instructors and skaters in the NMT group, many of the NMT exercises were sufficiently challenging to the point that they were barely attainable (but were attainable). Importantly, skaters, regardless of level, did not master the more difficult exercises by the end of the 6-week intervention. This would suggest that the NMT exercises were assigned at the appropriate level of difficulty. Ross et al. [39] observed a significant decrease in MVCOP for single leg stance following 6-weeks of coordination training (using wobble boards) in subjects with functional ankle instability (FAI). However, it is reasonable to assume that 16 training sessions over a period of six weeks may not have been a sufficient stimulus to elicit measurable improvements in a non-injured athletic population. On average skaters in the training group practiced 276 minutes/week on the ice (prior to baseline measurements) and underwent 80 minutes/week of NMT. Because the activity of figure skating itself incorporates NMT principles, 80 minutes of formal NMT may not have further enhanced their level of postural control. Interestingly, both groups improved their TTSz following training. This suggests that the TTSz during the SLL test is sensitive to change, but something other than the NMT was at least partly responsible for the observed change. While control subjects were not exposed to any study related intervention, many of them did participate in a variety of off-ice conditioning classes. All skaters likely increased their
total practice time during the summer intervention period due to increased availability in
the absence of school, though we did not confirm this with questionnaires.

The unexpected lack of relationship between skating experience and the
dependent variables MVCOP and TTSz may be explained by the basic nature of the SLS
and SLL tests. Kovacs et al. did find significant improvements in COP path length for
more challenging tests (e.g., a jump landing with eyes closed) following four weeks of
NMT. However, we argued that those tests did not accurately represent the functional
demands of figure skating. Figure skaters, in most cases, receive and interpret
somatosensory, vestibular, and visual feedback [13-14]. A functional and meaningful
improvement in postural control for figure skaters should be evident with full use of all
three major sensory systems. The SLS test was intended to act as a control exercise to
establish unperturbed levels of postural control that would be relatively unaffected by
previous experience. As such, it was very basic indicated by few failed attempts (4/85).
The SLL test, though, was intended to represent one of the most common and important
components of successful figure skaters, a jump landing. Compared to the SLS test, the
SLL test induced more failed attempts (16/97 vs. 4/85), which might indicate that it was
sufficiently challenging. However, the fundamental difference between low and high
level figure skaters is the number of rotations completed in the air during a jump [2].
Because our SLL test protocol did not require rotation, it may not have elicited the use of
postural strategies exclusively utilized by more advanced skaters.

A shortcoming of using force plate measures to indirectly assess level of postural
control is that it assumes the use of a particular postural strategy (ankle strategy). A
postural strategy refers to the type of stereotypical movement that is employed to compensate for disturbance of balance. While deviations of the center of mass (COM) remain within the base of support (BOS) an ankle or hip strategy may be employed in response to balance perturbations [15, 20]. However, once the COM deviates beyond its BOS a step must be taken (stepping strategy). The ankle strategy is the most common postural strategy and involves distal to proximal leg muscle activation resulting in movement of the COM in the sagittal plane [15, 21]. The hip strategy is generally recruited in response to large and fast disturbances or a relatively small base of support and involves proximal to distal trunk and thigh muscle activation [15, 21]. Any deviation from the use of an ankle strategy would reduce the correlation between force plate measures and postural control. Observationally, the skaters in this study appeared to mostly utilize the ankle strategy during the two testing periods for both the SLS and SLL tests. However, we, like previous studies of a similar nature, did not confirm this with more sophisticated methods. Electromyographic recordings could have confirmed a distal to proximal leg muscle activation pattern, thereby indicating the use of an ankle strategy [15, 21]. Also, a motion capture system could have identified joint angles at the ankle, knee, and hip.
Chapter 6: Conclusion

The 6-week NMT program offered in this study did not improve postural control with respect to MVCOP during the SLS and SLL tests. It is inconclusive what contribution the NMT program may have made to the observed improvement in TTSz as both the training and control groups improved to the same extent. In all likelihood, it was the suspected increase in on-ice training time (for skaters from both groups) during the summer intervention period, rather than NMT, that influenced TTSz. Surprisingly, NMT did not differentially influence skaters of different levels of skill or experience.

Furthermore, our results indicate no significant baseline correlation between years of competition experience, skating level, and hours of weekly on-ice practice with the dependent variables MVCOP and TTSz. We suggest that the SLL test protocol, lacking a rotation component, may not have elicited the use of postural strategies exclusively developed in, and utilized by, more advanced skaters. Though NMT did not conclusively improve postural control with respect to the variables measured in this study, it is unlikely that it was of no benefit. Future research should examine the effects of NMT on success in competition and incidence of injury.
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