Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program

S M Lephart, J P Abt, C M Ferris, T C Sell, T Nagai, J B Myers, J J Irrgang

Background: In order to improve neuromuscular and biomechanical characteristic deficits in female athletes, numerous injury prevention programs have been developed and have successfully reduced the number of knee ligament injuries. However, few have investigated the neuromuscular and biomechanical changes following these training programs. It is also largely unknown what type of program is better for improving the landing mechanics of female athletes.

Objectives: To investigate the effects of an 8 week plyometric and basic resistance training program on neuromuscular and biomechanical characteristics in female athletes.

Methods: Twenty seven high school female athletes participated either in a plyometric or a basic resistance training program. Knee and hip strength, landing mechanics, and muscle activity were recorded before and after the intervention programs. In the jump-landing task, subjects jumped as high as they could and landed on both feet. Electromyography (EMG) peak activation time and integrated EMG of thigh and hip muscles were recorded prior to (preactive) and subsequent to (reactive) foot contact.

Results: Both groups improved knee extensor isokinetic strength and increased initial and peak knee and hip flexion, and time to peak knee flexion during the task. The peak preactive EMG of the gluteus medius and integrated EMG for the gluteus medius during the preactive and reactive time periods were significantly greater for both groups.

Conclusions: Basic training alone induced favourable neuromuscular and biomechanical changes in high school female athletes. The plyometric program may further be utilised to improve muscular activation patterns.
Subjects
Twenty seven healthy, female athletes were recruited from local area high schools. Subjects provided written informed consent prior to participation in accordance with the University Institutional Review Board. Subjects were randomly assigned to either a plyometric or basic resistance group. Subject demographics (number of subjects, age, height, and mass) for each group are as follows: plyometric group (n = 14, 14.5 ± 1.3 years, 1.65 ± 0.06 m tall, and 55.1 ± 8.0 kg) and basic resistance group (n = 13, 14.2 ± 1.3 years, 1.66 ± 0.08 m tall, and 58.3 ± 10.8 kg). All subjects participated in nationally or locally organised basketball or soccer club teams. Subjects reporting a history of serious knee injury or other lower extremity injury within the previous 6 months were excluded.

Instrumentation
Isokinetic knee and isometric hip strength data of the dominant limb were collected with the Biodex System 3 Multi-Joint Testing and Rehabilitation System (Biodex Medical, Shirley, NY). Torque values were automatically adjusted for gravity by Biodex Advantage Software version 3.0 (Biodex Medical). Limb dominance was defined by the leg used to kick a ball.16 EMG activity of the dominant limb was measured with the Noraxon Telemyo System (Noraxon USA, Scottsdale, AZ). Pre-gelled bipolar (Ag/AgCl) surface electrode discs (Medicotest, Rolling Meadows, IL) were positioned on the muscle belly of the vastus medialis, vastus lateralis, medial hamstring, lateral hamstring, and gluteus medius. Visual inspection of the raw EMG signal was performed on an oscilloscope during an isolated manual muscle test to confirm correct positioning of the electrodes. EMG signals were passed from a portable battery operated FM transmitter worn by the subject to a receiver (gain 500, band pass filtered 15–500 Hz, common mode rejection ratio of 130 dB), converted from analog to digital data, and stored on a personal computer for processing. EMG data were sampled at a rate of 1200 Hz during both functional tasks. A maximal voluntary isometric contraction (MVIC) was collected for each muscle to be used for normalisation of the EMG during the data collection trials.

Raw coordinate and force data were collected using the Peak Motus 3D Motion Analysis System (software version 6.03, Peak Performance Technologies, Englewood, CO) interfaced with six high speed (120 Hz) optical cameras (Pulnix Industrial Product Division, Sunnyvale, CA) and an in-ground force plate (Bertec, Worthington, OH). The capture volume of 4.5 × 1.5 × 2.1 m³ was calibrated using a wand method (wand length 0.914 m) with a mean residual error range of 1.2–1.9 mm. Coordinate and force data were collected at 120 and 1200 Hz, respectively. Linear and circumferential anthropometric measurements of the dominant lower extremity were recorded for each subject. Retroreflective markers (diameter 0.025 m) were placed at designated anatomical landmarks as described by Vaughan et al.17 Two additional markers were attached to wands (at a distance of 0.09 m from the skin) and placed at the lateral side of the mid-thigh and mid-calf.

Protocols: peak torque and landing assessment
For knee strength testing, subjects were seated in the Biodex chair and secured using thigh, pelvic, and torso straps to minimise accessory and compensatory movements during the knee strength testing. The lateral femoral epicondyle of the dominant limb was aligned with the dynamometer’s axis of rotation. Subjects performed isokinetic extension and flexion concentric contractions at 60°/s and 180°/s after practice sessions. The peak torque was normalised with their body mass for the quadriceps and hamstrings for each speed. During MVIC for quadriceps and hamstrings testing, the testing leg was positioned at 45° of knee flexion, and the peak torque and EMG were recorded for 5 s.

Isometric hip abduction strength was assessed in a side-lying position with the centre of the greater trochanter aligned with the dynamometer’s axis of rotation. Subjects were secured using torso and pelvic straps. Subjects performed three 5 s maximal isometric contraction at 0° of hip abduction.
The jump-landing task (fig 1) consisted of a double legged vertical jump. Subjects were initially placed in a standing vertical position with the dominant limb on the force plate and the non-dominant limb on the floor. Subjects were instructed to perform a maximal effort vertical jump and land on the force plate. Subjects were provided with a verbal description and visual demonstration of the task, and practised to familiarise themselves with the tasks prior to the testing. Limited landing instructions were provided to promote natural performance of the task. Ten trials of each task were collected.

**Descriptions of the plyometric and basic programs** *(appendix A)*

An 8 week training protocol was designed specifically for female athletes to address previously identified deficient neuromuscular and biomechanical mechanisms that contribute to inadequate dynamic knee stability. Both the plyometric and basic training programs consisted of two, 4 week phases. Phase I was identical for both groups. It consisted of six lower extremity flexibility exercises (three repetitions each for 30 s), 11 resistance exercises (20–30 repetitions each), and three balance (fig 2) exercises (three repetitions each for 15 s). The plyometric group performed a different phase II than the basic group. Phase II for the plyometric group integrated 11 plyometric exercises (10 repetitions each) and seven agility training exercises (five repetitions each) into the existing training program. The basic training group’s Phase II progressed the phase I exercises by increasing the amount of time and number of repetitions for each exercise. Each exercise component was performed 3 days per week with the repetitions progressed between phases. Each training session typically took 30 min. Exercise logs, a verbal description, and video demonstration CD were provided for all subjects. Bi-monthly meetings were held with all subjects to ensure compliance and proper performance of the exercises.

**Data reduction**

Raw three-dimensional coordinate and analog data were exported to MS3D version 4.5 (MotionSoft, Chapel Hill, NC) for further processing. Raw three-dimensional coordinate data were filtered using a low pass Butterworth 4th order, zero lag digital filter with an estimated cut-off frequency. Vertical ground reaction forces were calculated following time synchronisation of coordinate and analog data. Joint centres of the hip, knee, and ankle were estimated using three-dimensional coordinates of the markers. Kinematic and kinetic variables were analysed throughout the movement cycle at initial contact and peak vertical ground reaction force.

**EMG data** were recorded 150 ms prior to initial contact with the force plate and 150 ms following initial contact with the force plate for the jump-landing task. The onset time was determined as the time when EMG voltage passed above the mean plus 3 standard deviations of the resting trials. The raw MVIC data were processed using a linear envelope (fullwave rectified and low pass filtered 4th order, zero phase lag Butterworth with a 20 Hz cutoff). The peak amplitude of a 30 ms moving average was calculated and used to normalise all trial data. The time to peak EMG amplitude was calculated and reported as the time before (preactivity) and after the initial contact (reactivity). The raw trial data were processed using a linear envelope (fullwave rectified and low pass filtered 4th order, zero phase lag Butterworth with a 20 Hz cutoff). Integrated EMG data were calculated for each time interval and reported as %MVIC*.

**Statistical analysis**

Data were analysed with SPSS 11.0 (SPSS, Chicago, IL). Separate two way (group × session) repeated measures ANOVA were performed to assess differences in strength, kinematic, kinetic, ground reaction force, and EMG data. Statistical significance of p < 0.05 was set a priori.

**RESULTS**

Strength data are presented in table 1. Both groups demonstrated a significant improvement in peak quadriceps strength at 60°/s (p = 0.007) and 180°/s (p = 0.006). No significant differences were noted in hamstring or hip abduction strength (p > 0.05) between tests. No significant group (plyometric vs basic) differences were found for any strength variables.

Kinematic, kinetic, and ground reaction force data during a jump-landing task are presented in tables 2–4. Kinematically, both groups significantly...
decreased the peak knee flexion moment \( (p = 0.013) \) and hip flexion moment \( (p = 0.008) \). No significant differences in vGRF were revealed between tests. No significant group differences existed for any kinematic, kinetic, or vGRF variables during the jump-landing task.

EMG jump-landing data are presented in tables 5 and 6. The peak preactive EMG of the gluteus medius \( (p = 0.008) \) was significantly heightened for both groups between tests. The area under integrated EMG for the gluteus medius during the preactive \( (p = 0.016) \) and reactive \( (p = 0.008) \) periods was significantly greater for both groups. There was an interaction effect on the peak reactivity EMG time of the medial hamstring \( (p = 0.028) \).

DISCUSSION

Quadriceps strength significantly improved for all subjects post-training, which is beneficial due to the noted quadriceps strength differences between males and females. The post-training peak quadriceps torques in the current study were similar to the previously reported values of Division I college female athletes. Although the hamstrings torque improved approximately 6–7%, the change was not significant. This finding is different from that reported by Hewett and colleagues\(^{14} \) who reported increased hamstrings torque after plyometric training. The differences observed between these two studies may be due to the differences in training protocols, intensity, and/or training duration.

Vertical ground reaction forces did not change significantly post-training in the current study, which was contrary to the hypothesis. Two studies have investigated the effect of plyometric training on vGRF, and both reported a reduction in vGRF after training.\(^{14, 21} \) Ground reaction forces are also influenced by the application of proper techniques, and have been reduced by as much as 20%.\(^{22, 23} \) It is unclear whether reduction in vGRF is due to the constant feedback (instruction effects) or actual neuromuscular adaptations. From an

![Figure 3](http://bjsportmed.com)

Figure 3  Peak knee flexion during jump-landing (pre-training v post-training). (Photographs reproduced with permission.)
activities has been reported to influence the body’s ability to
in hip adductor strength, the current finding was similar to
jumping task. Although we did not find significant changes
adduction and knee valgus during the landing portion of a
ground contact in anticipation of the impact forces at landing
indicated that subjects may position the thigh prior to
of the gluteus medius prior to the initial contact with the
mechanical advantage of the soft tissue structures to provide
more effectively absorb joint forces while promoting the
knee flexion during the jump-landing task enable the body to

**Table 6** Integrated EMG data

<table>
<thead>
<tr>
<th>EMG variables</th>
<th>Pretest [%MVIC]</th>
<th>Post-test [%MVIC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vastus lateralis</td>
<td>PLYOMETRIC</td>
<td>0.014 ± 0.008</td>
</tr>
<tr>
<td>proactivity</td>
<td>BASIC</td>
<td>0.019 ± 0.003</td>
</tr>
<tr>
<td>Vastus lateralis</td>
<td>PLYOMETRIC</td>
<td>0.064 ± 0.02</td>
</tr>
<tr>
<td>reactivity</td>
<td>BASIC</td>
<td>0.009 ± 0.026</td>
</tr>
<tr>
<td>Vastus medialis</td>
<td>PLYOMETRIC</td>
<td>0.016 ± 0.012</td>
</tr>
<tr>
<td>proactivity</td>
<td>BASIC</td>
<td>0.027 ± 0.015</td>
</tr>
<tr>
<td>Vastus medialis</td>
<td>PLYOMETRIC</td>
<td>0.088 ± 0.055</td>
</tr>
<tr>
<td>reactivity</td>
<td>BASIC</td>
<td>0.13 ± 0.024</td>
</tr>
<tr>
<td>Lateral hamstring</td>
<td>PLYOMETRIC</td>
<td>0.016 ± 0.018</td>
</tr>
<tr>
<td>proactivity</td>
<td>BASIC</td>
<td>0.017 ± 0.013</td>
</tr>
<tr>
<td>Lateral hamstring</td>
<td>PLYOMETRIC</td>
<td>0.035 ± 0.037</td>
</tr>
<tr>
<td>reactivity</td>
<td>BASIC</td>
<td>0.025 ± 0.013</td>
</tr>
<tr>
<td>Medial hamstring</td>
<td>PLYOMETRIC</td>
<td>0.014 ± 0.009</td>
</tr>
<tr>
<td>proactivity</td>
<td>BASIC</td>
<td>0.011 ± 0.007</td>
</tr>
<tr>
<td>Medial hamstring</td>
<td>PLYOMETRIC</td>
<td>0.026 ± 0.018</td>
</tr>
<tr>
<td>reactivity</td>
<td>BASIC</td>
<td>0.014 ± 0.006</td>
</tr>
<tr>
<td>Gluteus medius</td>
<td>PLYOMETRIC</td>
<td>0.019 ± 0.014</td>
</tr>
<tr>
<td>proactivity</td>
<td>BASIC</td>
<td>0.024 ± 0.013</td>
</tr>
<tr>
<td>Gluteus medius</td>
<td>PLYOMETRIC</td>
<td>0.038 ± 0.024</td>
</tr>
<tr>
<td>reactivity</td>
<td>BASIC</td>
<td>0.052 ± 0.03</td>
</tr>
</tbody>
</table>

*Significant main effect pretest-posttest differences at p<0.05.

Injury prevention standpoint, it is important to minimise
vGRF during landing, but stiffer landing and shorter foot
contact time are necessary for better athletic performance in
stretch-shortening cyclic movements such as running, bounding,
and repeated jumping. Future studies will be needed to address the relationship and roles of vGRF in
injury prevention and athletic performance.

Hip flexion at initial contact and peak knee and hip flexion
were increased in both groups, supporting our hypotheses. Increased hip flexion, peak knee flexion, and time to peak
correlation among the jump-landing task enables the body to
more effectively absorb joint forces while promoting the
mechanical advantage of the soft tissue structures to provide
joint stability. The degree of knee flexion during landing
activities has been reported to influence the body’s ability to
attenuate joint forces. Additionally, increased knee flexion
and hip flexion during landing tensions the hamstring muscles
to provide a posterior force upon the knee to protect
the ACL. This contention is further supported by the
increased peak hip and knee flexion moment during the
landing.

Improvements in integrated and time to peak EMG activity
of the gluteus medius prior to the initial contact with the
ground indicated that subjects may position the thigh prior to
ground contact in anticipation of the impact forces at landing
that would cause hip adduction and knee valgus. The
gluteus medius may enhance knee stability by limiting hip
adduction and knee valgus during the landing portion of a
jumping task. Although we did not find significant changes
in hip adductor strength, the current finding was similar to
that of a previous study, in which the authors reported
earlier only for the plyometric group, and the iEMG increased
27–46% in both groups. Vittasalo et al compared elite
jumpers and controls as regards jumping mechanics and
EMG, and reported much greater activation of the lateral
hamstring during the pre-landing phase. This EMG strategy
on the lateral hamstring is also apparent for ACL deficient “copers” who can participate in sports without any problems
or instability. This may be one advantage of including
some type of plyometric and jumping exercises in the
program to optimise the activation of the lateral hamstring
prior to foot contact. Recent computer injury simulation
studies reported that secondary rotations (valgus/varus
and internal/external rotations of the tibia) are responsible
for most non-contact ACL injuries. The role of secondary
rotations and muscular contributions to such rotations
should be investigated in the future.

The current study has several limitations. First, no “true”
control group was assessed, and the non-participating
subjects may have achieved similar neuromuscular adapta-
tions despite their non-participating group status. Second,
the current exercise programs were home based, and
although exercise performance was regularly monitored, true
compliance was unknown. Third, the 4 week volume of
agility and plyometric training for the plyometric program
may not have had sufficient time to induce an additional
neuromuscular and biomechanical benefit.

**CONCLUSION**

The results of this study suggest that the neuromuscular
characteristics of the lower extremity in female athletes can

**What is already known on this subject**

Numerous injury prevention programs have been developed
and have successfully reduced the number of knee ligament
injuries. However, few have investigated the neuromuscular
and biomechanical changes following these training pro-
grams. It is also largely unknown what type of program is
better for improving the landing mechanics of female
athletes.

**What this study adds**

The results of this study suggest that the neuromuscular
characteristics of the lower extremity in female athletes can
be improved with a basic exercise program alone, potentially
reducing at risk injury positions during a drop-landing. Additionally, a plyometric program may further be utilised to
improve muscular activation patterns.
Reports a reduction in injury rate after a strength training program alone. Additionally, a plyometric program may further be utilised to improve muscular activation patterns. Future research should examine the long-term effects of basic and plyometric or a combined program with an increased stimulus to promote dynamic knee stability. Only prospective studies involving a large number of participants will determine the true effects of plyometric and basic programs on ACL injuries in female athletes.

APPENDIX A

Table AI Phase I exercises: both groups (weeks 1–4)

<table>
<thead>
<tr>
<th>Exercise Type</th>
<th>Description</th>
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<tbody>
<tr>
<td>Flexibility, 3 repetitions (30 s)</td>
<td>Resistance, 20 repetitions</td>
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<tr>
<td>Quadriceps</td>
<td>Lateral step down</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>Calf raises</td>
</tr>
<tr>
<td>Hip flexors</td>
<td>Thera-band, leg curls</td>
</tr>
<tr>
<td>Tensor fascia latae</td>
<td>Theraband, leg extensions</td>
</tr>
<tr>
<td>Hip adductors</td>
<td>Theraband, squats</td>
</tr>
<tr>
<td>Calf</td>
<td>Abdominal curl ups</td>
</tr>
<tr>
<td>Balance, 3 repetitions (15 s)</td>
<td>Side bridging, bent knees</td>
</tr>
<tr>
<td>Single leg balance</td>
<td>Standing hip rotations</td>
</tr>
<tr>
<td>Single leg balance, flexed knee</td>
<td>Single leg hip hike</td>
</tr>
<tr>
<td>Single leg balance perturbations</td>
<td>Single leg hip hike</td>
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</table>

Table AII Phase II exercises: plyometric group (weeks 5–8)

<table>
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<td>Flexibility, 3 repetitions (30 s)</td>
<td>Resistance, 30 repetitions</td>
</tr>
<tr>
<td>Quadriceps</td>
<td>Single leg squat</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>Calf raises, single leg</td>
</tr>
<tr>
<td>Hip flexors</td>
<td>Thera-band, leg curls</td>
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<tr>
<td>Tensor fascia latae</td>
<td>Theraband, leg extensions</td>
</tr>
<tr>
<td>Hip adductors</td>
<td>Theraband, squats</td>
</tr>
<tr>
<td>Calf</td>
<td>Abdominal curl ups</td>
</tr>
<tr>
<td>Plyometrics, 10 repetitions</td>
<td>Single leg</td>
</tr>
<tr>
<td>Single/double leg forward hops</td>
<td>Single leg</td>
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<tr>
<td>Single/double leg broad jump</td>
<td>Single leg</td>
</tr>
<tr>
<td>Single/double leg jump from box</td>
<td>Forward lean hip rotations</td>
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<tr>
<td>Double leg backward hops</td>
<td>Agility, 5 repetitions</td>
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<tr>
<td>Double leg lateral hops</td>
<td>Shuttle runs</td>
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<tr>
<td>Double leg squat thrusts</td>
<td>45° cuts</td>
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<td>Double leg jump-lunge-jump</td>
<td>Butt kicks</td>
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<tr>
<td>Double leg jump from box</td>
<td>High knees</td>
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<tr>
<td>Scissors jumps</td>
<td>Side sliding</td>
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<tr>
<td>Triple hops</td>
<td>Caricots</td>
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<tr>
<td>Balance, 3 repetitions (10 s)</td>
<td>Standing hip rotations</td>
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<tr>
<td>Single leg balance</td>
<td>Single leg</td>
</tr>
<tr>
<td>Quadriceps</td>
<td>Single leg</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>Single leg</td>
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<tr>
<td>Hip flexors</td>
<td>Single leg</td>
</tr>
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<td>Single leg</td>
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<tr>
<td>Hip adductors</td>
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</tr>
<tr>
<td>Calf</td>
<td>Single leg</td>
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REFERENCES


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