Impact Attenuation and Variability During Running in Females: A Lifespan Investigation

Janet S. Dufek, John A. Mercer, Kaori Teramoto, Brent C. Mangus, and Julia A. Freedman

Context: Impact is known to cause injury during running, while variability is thought to promote healthy performance. Objective: Quantify contributions of the lower extremity and back and the variability of impact generation among (1) prepubescent girls (Grp 1), (2) normally menstruating women (Grp 2), and (3) postmenopausal women (Grp 3) to address possible lifespan changes during running. Design: A mixed model experiment. Setting: Biomechanics Laboratory. Participants: 31 healthy females owing membership to Grp 1, Grp 2, or Grp 3. Intervention. Participants ran on a treadmill at their preferred speed (45 s) and at a speed 10% faster (45 s) while instrumented with uniaxial accelerometers. Main Outcome Measures: Lower extremity attenuation, back attenuation and variability of peak impact acceleration values. Results: Lower extremity attenuation and variability were greatest for Grp 1 while impact variability was least for Grp 2. Conclusion: Lifespan phases appear to affect impact attenuation strategies and variability of impact during running for females.

The human body, at all stages throughout the lifespan, is a very complex machine that has numerous degrees of freedom and therefore multiple movement options available to complete any given motor task. Each time a person performs a task, the movement is never done in exactly the same way, thus there is a new experiential pool from which to select options. Newell and Corcos1 specified that such movement variability is pervasive and exists both within and between individuals. The concept of variability relative to running performance and sample size was initially explored by Bates et al2,3 and has more recently been revisited relative to impact activities including locomotion and landing by various research teams.4–8 Specifically, it has been reported that disruption of timing and motion of the lower extremities during running is associated with injury.9 A decrease in variability of lower extremity coupling (LEC), the evaluation of the interactions between and among segmental displacement, velocity and temporal relationships, has been associated with running injury.4-6 In an explanatory sense, the lack of variation in LEC

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may result in similar stress being repeatedly applied to tissue, resulting in overuse injury. Meardon et al\textsuperscript{10} explored LEC variability using continuous relative phase variability for a group of individuals with a history of iliotibial band syndrome and concluded lesser variability appeared to be exhibited by the injured subjects. This research suggests that injury propensity may increase with a pattern of reduced variability of performance. This is in agreement with previous literature relative to biological heart rate variability,\textsuperscript{11,12} which suggested lesser variability in cardiac function may be related to a greater incidence of coronary dysfunction. The corollary hypothesis in the human movement domain is that increased performance variability may lead to a lesser propensity for lower extremity injury. By specific example, a slight change in the orientation of the resultant force vector during running will result in a unique force application, from the body’s perspective, thereby potentially reducing the risk of cumulative trauma and potential injury. We believe, as others have postulated, that further exploration of this concept with respect to women’s health is necessary as it may be an underlying functional performance mechanism tied to injury occurrence. Pediatric injury rates have shown that 30% to 50% of all sports injuries are due to overuse.\textsuperscript{13} Also, female runners have been shown to be more susceptible to stress fractures than males, which has been attributed to hormonal factors and lower bone mineral density.\textsuperscript{14} Extending this notion to the postmenopausal population, we sought to embrace a “lifespan” approach to our interest in exploring women’s health and specifically performance variability.

Spatial-temporal characteristics of walking gait (eg, stride time, gait speed) have been shown to vary across time and between consecutive strides, even when controlling external environmental conditions.\textsuperscript{15} These outcome measures can be categorized in the same family of measures as are explored during LEC evaluations, i.e., kinematic measures. Kinetic measures have yet to be similarly evaluated for female runners. We question whether understanding variability of peak impact acceleration values (kinetic measures) during running can lend insight into injury predisposition and/or injury prevention for females.

The activity of running is a learned skill that once acquired, requires little cognitive attention to perform repeatedly. A common variation to the task of running, such as speed modification, can also be performed easily within physiological limits of the performer. The consistency or repeatability of the task of running at any given speed can be evaluated by quantifying variability of performance either within an individual or across heterogeneous classifications or groups of individuals. From an injury perspective, one can argue that increasing variability while maintaining skilled performance may be beneficial as slight modifications in performance would modify the direction of the force vector on the body and as such, the magnitude and direction of force which the tissues of the body experience. James et al\textsuperscript{16} presented this concept of variability with respect to healthy and potentially injurious performance, suggesting that the bandwidth of variability may be unique to any one individual and that an available channel of performance or range of safe performance exists for all movements. In addition, James\textsuperscript{17} suggested that lesser variability may be related to a greater likelihood of overuse injury, with a caution that excessive variability may lead to unique or aberrant behavior and a possible acute injury. Of interest is whether a channel or bandwidth of performance variability is consistent among homogeneous group members (ie, maturation classifications of females) and inconsistent between or among heterogeneous groups. We sought to explore
this relationship during running using peak impact acceleration values and impact attenuation as our measures of change in performance and variability.

During adult running, there are approximately 2500 collisions between the runner’s foot and the ground for each 30 min of running. With each foot-ground collision, a shock wave of energy is transmitted throughout the body with adult runners absorbing, via bone and soft tissue, about 80% of the impact during running.18–20 Researchers21,22 have suggested that the geometry of the lower extremity at contact may affect how this shock is attenuated throughout the body and this lower extremity geometry can be modified with changes in running speed. An examination of the shock wave generated at foot-ground contact and how it is attenuated throughout the body may lend insight into injury prevention. We examined impact attenuation characteristics for specific groups of physically active females during running by measuring the impact shock (generated by the foot-ground collision) and evaluated how it was attenuated throughout the body by the performer. Coupling our interest in exploring possible unique strategies of impact attenuation in females along with the notion that variability of performance might be related to this outcome, the specific aims of the research were to (1) examine the impact attenuation strategies for preferred and fast running among prepubescent girls (Grp 1), normally menstruating women (Grp 2), and postmenopausal women (Grp 3) and (2) explore variability characteristics of maximum impact acceleration values at the leg, low back, and head between and among these same heterogeneous groups of women at two speeds as a possible mechanism to explain lower extremity injury propensity in females. Relative to aim 1, we hypothesized that impact dissipation would be greatest for Grp 1, arguing that young girls function in an immature physical body with greater plasticity of biological tissue and therefore greater ability to absorb impact energy. In addition, this impact dissipation would increase with an increase in running speed, as a result of greater leg impact values. Relative to aim 2, we hypothesized that variability would be greatest for Grp 1, contending that their need to seek alternative motor solutions, as well as their lesser developed motor patterns, would overshadow the plasticity of their developing neuro-musculo-skeletal system and ultimately result in increased variability. We hypothesized that the activity of running would be most variable for Grp 1 as they continued to “solve” the movement problem presented for the upcoming step, which is influenced by the preceding step. We further hypothesized that this variability would be greater during the fast running speed condition.

Methods

Subjects

Thirty-one females with experience in jogging/running activities, free from lower extremity injury (Table 1), falling into one of three groups, premenarche girls (Grp 1, n = 11), normally menstruating women (Grp 2, n = 12) and postmenopausal women (Grp 3, n = 8), granted written informed consent to participate in the study as approved by the Institutional Review Board for protection of human subjects at the affiliated university. Written consent was provided by a parent of the minor girls. Since our research interests lied in the generalized group membership and not
physiological changes associated with the female menstrual cycle, subjects were classified based upon their membership into one of the three discrete experimental groups independent of subject-specific hormonal levels or menstrual phases. Upon granting consent, subjects were allowed time to practice running on a treadmill (Precor, Model C966) to become familiar with the environment as well as to establish their preferred running speed, defined as a pace that they could maintain for 20 min of continuous running.

**Instrumentation**

Following treadmill familiarization, subjects were instrumented with three lightweight uni-axial piezoelectric accelerometers (PCB Piezotronics Inc., Model 352C68) placed on the distal aspect of the right tibia, low back at approximately the fifth lumbar vertebrae and the frontal aspect of the forehead to measure segmental impact acceleration. Accelerometers were secured as tightly as possible to the respective anatomical sites. The tibial accelerometer was secured with stretchable bandage tape. A molded orthoplast shroud in combination with a weight belt was used to secure the accelerometer at the back and limit its motion. An adjustable plastic headband was used to secure the head accelerometer on the central forehead. Accelerometers were interfaced through a Type 9865B 8 channel amplifier to a data acquisition system using Bioware software (Kistler Instrument Corp., Version 3.21).

Following instrumentation, subjects completed a final warm-up before running at their preferred speed for 45 s, during which time accelerometer data were obtained (1000 Hz). This was followed by a second running bout at a speed 10% faster than their preferred speed for an additional 45 s during which time accelerometer data were similarly obtained.

**Data Reduction**

Peak acceleration values during the impact phase were extracted from 10 running strides at each measurement site for each subject-condition: peak tibial impact acceleration (LgPk), peak back impact acceleration (BkPk), and peak head impact acceleration (HdPk). The coefficient of variation of each of these impact values by condition was calculated for each group, defining three variability measures (LgCV, BkCV, and HdCV, respectively). Two additional dependent variables (DVs), lower extremity percent attenuation (LE%) and back percent attenuation (Bk%) were defined and calculated as follows:

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LE\% = 100 - ([BkPk / LgPk] \times 100)
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\[
Bk\% = 100 - ([HdPk / BkPk] \times 100)
\]

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Menarche (n = 11)</td>
<td>9.2 (1.9)</td>
<td>139.9 (12.5)</td>
<td>32.9 (7.7)</td>
</tr>
<tr>
<td>Normally Menstruating (n = 12)</td>
<td>25.2 (3.9)</td>
<td>164.3 (3.2)</td>
<td>63.6 (9.2)</td>
</tr>
<tr>
<td>Post-Menopausal (n = 8)</td>
<td>53.2 (6.1)</td>
<td>163.0 (8.2)</td>
<td>67.2 (13.0)</td>
</tr>
</tbody>
</table>

Table 1 Subject Characteristics (Mean ± Standard Deviation)
These latter two DVs, normalized to the respective distal anatomical measurement site, were representative of impact attenuation characteristics of the biological system. That is, the attenuation characteristics of the lower extremity compared with the back/vertebral column could be compared to identify differences in mechanisms of impact dissipation between speeds and among groups.

### Statistical Analysis

Sample size was determined a priori using laboratory shelf data previously obtained from male child runners for LgPk / HdPk ratios only and applying the techniques outlined by Howell. The results of this power analysis indicated that 90% statistical power could be obtained with n = 10 per group. Since this analysis was completed for male child runners and the current work focused on female runners, we strove to obtain 11 subjects per group, owing to unknown potential gender differences. Following data collection, it was detected that one participant had been misclassified, and a data collection error (movement of the back accelerometer) for two members of Grp 3 resulted in unequal sample sizes. All statistical analyses were conducted using techniques accounting for unequal n.

The study incorporated a two-factor (group × speed) mixed model design with speed as the repeated (within-subject) factor. Impact attenuation characteristics among groups were evaluated using general linear model analyses of variance (ANOVA) techniques for each DV (Lg%, Bk%). Variability of running performance was similarly assessed for the coefficient of variation measures (LgCV, BkCV, HdCV). When appropriate, Scheffé follow-up tests were conducted to identify simple main effect differences. Level of significance was set at \( \alpha = .05 \) for all statistical tests. All tests were conducted using SAS statistical analysis software.

### Results

#### Impact Evaluation

Descriptive data for the impact acceleration measures (LgPk, HdPk, BkPk) as well as running speed by group-condition are given in Table 2. An exemplar impact acceleration-time history is illustrated in Figure 1. Results of the mixed model ANOVAs for both impact DVs (Lg%, Bk%) identified no significant group x speed interactions \((P > .05)\) nor significant speed effects \((P > .05)\). Significant group differences were identified for Lg% \((F_{2,28} = 3.58, P < .0414)\) while no significant differences were identified for Bk% \((P > .05)\). Follow-up Scheffé tests for Lg% identified significant \((P < .05)\) differences between Grp1 and Grp 2 as well as Grp 1 and Grp 3. The comparative segmental contributions to impact attenuation for each group are illustrated in Figure 2.

#### Variability Assessment

Coefficient of variation (CV) of the impact values was used to quantify performance variability among the groups during running. Results of the mixed model ANOVAs for the variability measures identified no significant group × speed interactions
Table 2  Peak Impact Mean (± Standard Deviation) Values by Group-Condition

<table>
<thead>
<tr>
<th>Variable</th>
<th>Grp 1</th>
<th>Grp 2</th>
<th>Grp 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preferred</td>
<td>Fast</td>
<td>Preferred</td>
</tr>
<tr>
<td>LgPk</td>
<td>4.87</td>
<td>6.07</td>
<td>4.36</td>
</tr>
<tr>
<td></td>
<td>1.88</td>
<td>2.41</td>
<td>1.32</td>
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<tr>
<td>BkPk</td>
<td>2.25</td>
<td>2.50</td>
<td>2.68</td>
</tr>
<tr>
<td></td>
<td>0.77</td>
<td>0.93</td>
<td>0.94</td>
</tr>
<tr>
<td>HdPk</td>
<td>1.23</td>
<td>1.36</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>0.68</td>
<td>0.64</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Note. LgPk = Leg Impact Acceleration Peak; BkPk = Back Impact Acceleration Peak; HdPk = Head Impact Acceleration Peak.

Figure 1 — Exemplar acceleration-time history for each of the three (leg, back, head) anatomical sites evaluated.
Lower Extremity Impact Attenuation

![Lower Extremity Impact Attenuation Graph]

Back Impact Attenuation

![Back Impact Attenuation Graph]

**Figure 2** — Segmental contributions to impact attenuation by group and speed. Figure 2a illustrates comparative results of LE% between speeds while Figure 2b illustrates comparative results of Bk% between speeds. Note: * = significant difference between Grp 1 vs Grp 3 ($P < .05$); # = significant difference between Grp 1 vs Grp 2 ($P < .05$).

($P > .05$) nor significant speed effects ($P > .05$). Significant group differences were identified for all variability measures: LgCV ($F_{2,28} = 3.91, P < .0318$), BkCV ($F_{2,28} = 10.38, P < .0004$) and HdCV ($F_{2,28} = 3.72, P < .0368$). Follow-up Scheffé tests, collapsed across the nonsignificant speed effect for LgCV and BkCV identified significant ($P < .05$) differences between Grp1 and Grp 2 as well as Grp 2 and Grp 3. Follow-up Scheffé tests for HdCV identified significant differences between Grp 1 and Grp 2. Variability by anatomical site for each group is illustrated in Figure 3.
Figure 3 — Variability by anatomical site. Figure 3a illustrates variability among groups and measurement sites for the preferred running speed. Figure 3b illustrates variability among groups and measurement sites for the fast running speed. Figure 3c illustrates site-by-group variability collapsed across the nonsignificant factor of speed. Note: # = significant difference between Grp 1 vs Grp 2 ($P < .05$); @ = significant difference between Grp 2 vs Grp 3 ($P < .05$).
Discussion

Impact Characteristics

The design of the study elicited an anticipated response for speed with all groups exhibiting greater peak impact values at all sites during faster running (Table 2), which is consistent with previous literature reporting shock attenuation (ratio relationship of LgPk and HdPk) values. In the current study, we sought to explore possible mechanistic differences among groups elicited by the change in running speed; however, the increase in speed invoked (10%) was not great enough to elicit significant changes for this group of runners. This may be attributed to the fact that the originally selected “preferred” speed was not fast enough such that the 10% increase did not “push” the participants into adopting a different strategy of running.

We sought to examine differences among groups relative to the structures of the body that attenuate the shock wave generated at foot strike during running. Results identified a significantly greater percentage of impact was absorbed by the lower extremities for Grp1 as compared with Grp 2 and Grp 3. Hass and colleagues identified differences in the biomechanics of the knee joint during landing for pre- and postpubescent females. They concluded that developmental changes influence knee joint mechanics during landing for females. The current study is in agreement with Hass et al and extends this notion to demonstrate that such differences for females may be specifically between the immature vs mature skeleton, supported by the lack of significant differences in Lg% between Grp 2 and Grp 3 (mature skeletons). Our hypothesis that the plasticity of the children’s soft tissue and skeletal structure would lead to an impact attenuation strategy that was different from the mature skeletons of the adult runners was supported with respect to the role of the lower extremities in attenuating impact.

While there were no significant differences identified among groups for Bk%, it can be observed that the total percent of impact attenuated during running decreased with age (Figure 2) for these female runners. To explore this apparent trend and owing to the nonsignificant main effect of speed, we repeated this analysis collapsing across the nonsignificant (speed) factor. Results of the univariate ANOVA identified a significant group effect ($F_{2,59} = 3.81, P = .0277$) for Bk% with Scheffé follow-up tests identifying significant ($P < .05$) differences between Grp 1 and Grp 2 (Figure 4). These data identify a strategy of impact attenuation unique to Grp 2 in that this group of runners attenuated the greatest percentage of the running shock wave via the spine (vs lower extremities). The effects of aging on spine health and specifically menopause on bone mineral density have been documented. As the vertebral column ages, disc space also decreases. These facts support the observed result of decreased Bk% for Grp 3 (vs Grp 2). The differences observed between Grp 1 and Grp 2 may be explained by the previously discussed result that Lg% was greatest for Grp 1. It has been previously reported and supported with the current study sample that runners generally optimize HdPk values to approximately 1.0 g. It can be observed that HdPk values were highest for Grp 1, which may explain the lesser Bk% for this group. That is, Grp 1 did not exhibit a similar strategy of utilizing the vertebral column to absorb impact that was apparently adopted by Grp 2 and Grp 3.
The magnitude of the LgPk and HdPk values observed for the female runners in the current study were generally less than those reported for male runners.\textsuperscript{20} However, the average running speeds across groups (2.43, 2.79 and 2.00 m/s for Grp 1, Grp 2 and Grp 3, respectively) were less than those for the male runners (3.2 to 6.4 m/s) in the Mercer et al study.\textsuperscript{20} Similarly, impact attenuation values for our female runners were less than those for male runners,\textsuperscript{18} yet the general trend to optimize/stabilize HdPk was observed for the female runners, similar to results previously reported for male runners.\textsuperscript{20} It should be noted that Grp 1 did not minimize HdPk to the levels observed by Grp 2 and Grp 3 (Table 2). In support of this observation, Grp 1 exhibited the least Bk\% (Figure 4) in comparison with Grp 2 and Grp 3, suggesting a unique impact attenuation strategy for Grp 1. A limitation in the current study may be the slower running speeds elicited from these female runners, negating the ability to make direct gender performance comparisons to what has been presented in the literature.

**Variability Characteristics**

The variability assessment was conducted relative to discrete points (maximum acceleration values) throughout the support phase of running at each of three anatomical measurement sites (leg, back, head). This is in contrast to some contemporary variability assessment techniques that compare temporal phasing between lower extremity segments.\textsuperscript{4,6,10} The current study did not investigate lower extremity kinematics and as such, focused on the central research question that related to how the body accommodated to impact. Therefore, the maximum impact values observed and their associated variability across conditions was evaluated to lend insight into general performer variability and not segmental comparative (ie, LEC) variability.

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**Figure 4** — Impact attenuation collapsed across speed. A significant ($P < .05$) difference was identified for Bk\% with Grp 2 being significantly greater than Grp 1. Note: # = significant difference between Grp 1 vs Grp 2 ($P < .05$); $\$ = significant difference between Grp 1 vs Grp 2 and Grp 3 ($P < .05$).
Across all impact variables, both Grp 1 and Grp 3 consistently exhibited greater variability (as expressed by the CV) in impact characteristics compared with Grp 2 (Figure 3). Keeping in mind the impact results previously reported, this observed result supports the notion presented by James et al\textsuperscript{16} that there may be a “channel” of variability appropriate for an individual to perform in and suggests that perhaps the bandwidth of this safe (injury-free) performance zone is lesser for Grp 2 versus Grp 1 and Grp 3. This conjecture also follows the work of Goldberger et al\textsuperscript{11,12} with respect to heart rate variability which indicated that individuals who experienced ventricular fibrillation exhibited a very narrow band of cardiac dynamics, as opposed to healthy counterparts. Hamill et al\textsuperscript{4} examined lower extremity kinematic variability for a group of injured (patellofemoral pain) runners vs healthy controls and identified greater variability for the noninjured group. They went on to suggest, similar to James et al,\textsuperscript{16} that the injured runners seemed to perform within a very narrow range (“channel” of variability). Our hypothesis that Grp 1 would exhibit the greatest variability in peak impact acceleration values was supported. Furthermore, since Grp 2 consistently exhibited lesser variability, a reasonable suggestion is that Grp 2 be trained to vary their kinematics of running via slight alterations in extrinsic factors such as footwear, running surface, or speed\textsuperscript{28} and not by consciously attempting to lengthen or shorten the stride, exhibit greater or lesser knee joint flexion or change trunk inclination. Rather, we suggest very subtle changes in the running environment to slightly change the impact magnitudes experienced at various anatomical locations (increase variability), in an attempt to minimize lower extremity injury potential.

Meardon et al\textsuperscript{10} explored variability of LEC, focusing on tibial rotation and its role in running for healthy versus injured runners. Similar to previous research,\textsuperscript{4,6} the results generally supported the trend that the injured runners were less variable in their kinematic patterning. The current work extends this notion with an examination of variability of kinetic loading. All runners in the current study were healthy but differed in their physical maturation. Grp 2 exhibited lesser variability than Grp 1 and Grp 3 across all DVs. Whether this observed outcome is the result of group membership or a reflection of kinematic differences, suggesting Grp 1 and Grp 3 would display more variable LEC patterns, cannot be answered with the current study results. This presents a limitation and deserves future research attention.

**Conclusion**

Results suggest that lifespan development influences both impact attenuation strategies and variability of peak impact acceleration values for female runners. It was observed that impact characteristics during running for females across the lifespan was consistent relative to group membership; however, the ability to attenuate the impact appeared to be greatest for Grp 1 and least for Grp 3, identifying an area of suggested future inquiry. Variability assessment among groups identified the greatest impact variability measures for Grp 1 and Grp 3, suggesting that Grp 2 may be at a higher risk of lower extremity injury, versus Grp 1 and Grp 3, if one ascribes to the notion as suggested in the literature,\textsuperscript{4,10,16,28,29} that increased variability of performance, within a band of skilled movement, is a desirable outcome relative to injury prevention. Further research is warranted to identify specific characteristics prevalent for each group which define observed strategy differences.
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References


