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Original research

Age and running experience influence shock attenuation during human running

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ABSTRACT

Objective: This study examined the associations of age and running experience with shock attenuation during running, as age and experience may influence passive (body composition) and active (gait) shock attenuation mechanisms.
Design: Cross-sectional study.
Methods: Participants included healthy middle-aged–experienced runners ($n = 20$, age: 52.95 ± 5.83 years, >1 year of experience, 9–30 mi·week^{-1}), young–experienced runners ($n = 24$, age: 22.37 ± 4.09 years, >1 year of experience, 9–30 mi·week^{-1}), and young–novice runners ($n = 14$, age: 22.50 ± 3.52 years, <1 year of experience, 3–13 mi·week^{-1}). Participants ran overground at 3.35 m·s^{-1} while triaxial accelerometers measured tibial and low-back impact shock. Frequency-domain axial and resultant shock attenuation was calculated using a transfer function within 3–8 Hz (FB1), 9–20 Hz (FB2), 21–35 Hz (FB3), and 36–50 Hz (FB4) bins. Linear regression tested associations of age among experienced runners and experience among young runners with each dependent variable ($\alpha > 0.05$).
Results: Middle-aged–experienced runners attenuated less resultant shock within FB1 ($p = 0.02$, 95 % confidence interval: 1.27–18.71, $\beta = 9.99$) and axial shock within FB2 ($p = 0.04$, confidence interval: 0.40–37.37, $\beta = 28.89$) and FB3 ($p = 0.005$, confidence interval: 17.02–91.71, $\beta = 54.37$) than young–experienced runners. Young–novice attenuated less axial shock within FB3 than young–experienced runners ($p = 0.02$, confidence interval: 6.72–92.13, $\beta = 49.43$).
Conclusions: Age and running experience independently influence shock attenuation, suggesting different shock attenuation responses between runner sub-populations.
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Practical implications

- Age and running experience affect frequency domain shock attenuation during running.
- Experienced middle-aged compared to young runners attenuate less axial shock within 9–35 Hz, while young novice than experienced runners attenuate less axial shock within 21–35 Hz.
- Running experience may not influence the degree to which age influences shock attenuation.
- Runner sub-groups may have unique biological tissue and gait responses to impact shock.
- A "one size fits all" training program is likely unsuitable to optimize tissue responses to running, and program prescriptions should account for a runner's age and running exposure.

1. Introduction

Novice and masters runners, including middle-aged runners, develop significantly more running-related injuries (RRIs) than experienced and young runners.[1–3] Novice runners of any age may cease running due to RRI development,[4] leading to a decline in physical activity which may contribute to decrements in musculoskeletal function that occur naturally with aging.[5] Thus far, RRI risk factors have been primarily identified among young, experienced runners, limiting generalizability to middle-aged and less-experienced runners who likely have different gait patterns and body composition. To minimize the adverse effects of RRI development among middle-aged and novice runners, RRI risk factors

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must be explored in these sub-populations. Peak impact shock at the tibia is a proposed risk factor among young, more-experienced runners.[6,7] However, the magnitude of this shock may not dictate prospective injury risk.[8] Instead, shock attenuation may be relevant to injury development because musculoskeletal structures absorb the impact shock as it propagates from the tibia to the head[9,10] contributing to tissue stress/microdamage that could eventually accumulate into tissue failure, as observed in animal specimens.[11] Shock transmission has been linked to musculoskeletal pain and disruption of the vestibulo-ocular reflex and is therefore modulated through both active and passive mechanisms.[13,15,16] Given that both age and running experience alter gait and body composition,[19,20,21,22] analyzing shock attenuation among novice and middle-aged runners may elucidate whether shock attenuation demands placed on musculoskeletal structures differ between runner sub-populations.

Changes to gait and musculoskeletal tissues with age and running experience may influence shock attenuation and its active and passive mechanisms; passive structures like musculoskeletal tissues, footwear, and ground substrate compliance attenuate higher-frequency shock related to the forces generated at foot–ground contact, while active attenuation of lower frequencies is achieved through eccentric muscle actions and related gait mechanics.[24,27,28] Gait mechanics like stance phase knee flexion, flexion–extension range of motion, and negative mechanical work during running decrease with age.[19,29] These changes with age may diminish the reliance on active shock attenuation of 3–8 Hz signal components, a range previously described as "lower frequencies",[25,30] via the stretch of elastic components in the muscle–tendon complex.[31] In turn, middle-aged runners may increase their reliance on passive attenuation via musculoskeletal tissues (e.g., bone, fat, inactive muscle) that attenuate higher frequency shock during running,[32] where "higher frequencies" often refer to frequencies >9 Hz.[25,28,30] These tissues decrease in mass and resiliency with age,[33,34] so a greater reliance on passive rather than active attenuation among middle-aged runners may overload these tissues and result in RRI development.

Like with aging, the gait mechanics of novice runners indicate a greater reliance on passive attenuation mechanisms than active compared with more-experienced runners. Depending on sex, less-experienced runners run with smaller knee flexion and ankle eversion magnitudes throughout stance than more-experienced runners[18,20] which suggests less negative mechanical work and reduced active shock attenuation by novice runners. Given that mass and resiliency of rigid and soft tissues improve with long-term exposure to weight-bearing exercise,[21–23] novice runners' tissues may be inadequately adapted to meet large shock attenuation demands. A potential shift in attenuation responsibilities from active gait to passive tissue mechanisms with increasing age and less running experience may increase RRI risk to passive tissues among middle-aged and novice runners.

Assessing the relationship between age, running experience, and shock attenuation is necessary to identify factors contributing to greater RRI rates with age and less running experience.[1–3] This study aimed to estimate the independent effects of age and running experience on the shock attenuation in the frequency-domain, with frequency bands representing active and passive attenuation: 3–8 Hz (FB1), 9–20 Hz (FB2), 21–35 Hz (FB3) and 36–50 Hz (FB4). While FB1 and FB2 have been analyzed as low and high frequency ranges previously, frequencies related to running-related impact can extend to 50 Hz[24,25,28] and were therefore analyzed in this study. Middle-aged runners run with less stance phase knee flexion, flexion–extension range of motion, and negative mechanical work during running than their younger counterparts[19,29]; therefore, they were hypothesized to attenuate less shock actively (within FB1) but more shock passively (within FB2–FB4) compared with young runners. Similarly, novice runners were hypothesized to attenuate less shock within FB1 but more shock within FB2–FB4 than experienced-runners because they run with reduced knee flexion and ankle eversion magnitudes throughout stance.[18,20]

2. Materials and methods

2.1. Sample characteristics

Forty-four participants were enrolled to meet a-priori power calculations for age ($f^2 = 0.18$, α error probability = 0.05, power = 0.80, required sample size = 40) and running experience ($f^2 = 0.46$, α error probability = 0.05, power = 0.80, required sample size = 19) using the vertical ground reaction force impact peak effect size from Bus[35] and peak tibial shock data from Camelio, Gruber, Powell and Paquette,[36] respectively.

Three sets of independent groups were recruited to test the independent effects of age and experience on shock attenuation. Experience was operationally defined using both weekly running volume (current $km \cdot week^{-1}$) and years running. The young–experienced group was the reference group for both tests. This group was 18–30 years old with >1 year of running 15–50 $km \cdot week^{-1}$. Independent effects of age were tested by comparing the reference group to the middle-aged–experienced group (45–65 years) who met the same experience criteria as the reference group. Independent effects of experience were tested by comparing the reference group to the young–novice group who were 18–30 years old with <1 year of running 4–20 $km \cdot week^{-1}$. The running experience criteria were based on the "recreational" and "novice" groups in Honert, Mohr, Lam and Nigg.[37] The following criteria adjustments were made to allow enrollment of those who ran for one year precisely or those who met criteria for either running-years or weekly mileage, but not both: Individuals who ran for exactly one year were included as either novice (n = 3) or experienced (n = 1) if their weekly mileage was within ±1 standard deviation of the mean for the other participants in the given group. Additionally, eight runners qualified as experienced per the running-years criteria but not weekly mileage criteria, while the opposite was true for one runner. These participants were classified as experienced if they had been running for >1 year (n = 8) and novice if they ran for <1 year (n = 1).

Participants self-reported their age, running injury history, total years of running, current weekly running volume ($km \cdot week^{-1}$), and readiness for physical activity to determine eligibility. For inclusion, participants had to be free of chronic disease or illnesses that may disallow engagement in ≥15 min of low to moderate-intensity physical activity, have no history of low-back or lower limb orthopedic surgery in the past ten years, and no musculoskeletal injury within the past six months or resumed normal running training volume for ≥8 weeks before enrollment if sustaining an injury within the past six months. Tobacco users and women pregnant at the time of the study were excluded. All testing procedures were approved by the university's Institutional Review Board, and all participants gave their written informed consent prior to participation.

2.2. Experimental protocol

Participants wore form-fitting clothes and lab-standard neutral running shoes (Reebok; One X CrossFit Cushion 3.0) to control for footwear effects on shock attenuation. Subject height and weight were measured, and then they performed a 5–8-minute warmup at their preferred running speed.

Segmental accelerations of the pelvis and lower leg were quantified with inertial measurement units (IMUs) (Blue Trident IMU, IMeasureU, Auckland, New Zealand; ±200 g, 12 g) containing triaxial accelerometers sampling at 1600 Hz. IMUs were affixed bilaterally to the boniest aspect of the skin over the anteromedial distal tibia and the low-back (i.e., lumbosacral joint). IMUs were secured using self-adhesive tape and elastic straps tightened as firmly as possible yet to the subject's comfort. The orientation of the IMU axes was aligned as follows: X-axis as axial (upward = positive), Y-axis as mediolateral (right = positive), and Z-axis as anterior–posterior (anterior = positive).

Participants performed a jump at the start of each running trial, for which the landing was manually flagged in the software capturing

force plate data (Qualisys Track Manager, Qualisys AB, Göthenburg, SWD). This manual flag was used later to temporally align the force plate and IMU data and identify the acceleration signals for the analyzed stance phases. Immediately following the jump, participants ran overground at the criterion speed (3.35 $m \cdot s^{-1} \pm 5$ %) along an 18-meter runway with three embedded force plates sampling at 1200 Hz (OR-6-2000; AMTI Inc., Watertown, MA, USA). A criterion running speed was employed across participants to minimize the known effects of running speed on impact shock and attenuation.[38,39] Running speed was monitored using two optoelectrical timing gates (TC-Gait, Brower Timing System, Draper, UT, USA) placed 6 m apart in the center of the runway. Each participant completed a minimum of eight successful running trials for each limb. Trials were successful if participants ran within ±5 % of the criterion speed, maintained constant speed between timing gates, avoided gait modification to target force platforms, and contacted the force platforms with their entire foot.

2.3. Data processing

2.3.1. IMU data

Acceleration data from the tibia and low-back IMUs along the axial (x-axis), anterior–posterior (z-axis), and mediolateral (y-axis) axes were extracted and exported to MATLAB (Release 2022a, MathWorks, Natick, MA, USA) for processing. The signals were not filtered. Each signal was converted from $m \cdot s^{-2}$ to units of gravity (g) and detrended by subtracting a least-squares best-fit line to remove any existing linear trend in the data. Signal bias was removed by subtracting the signal's mean from each data point such that the signal oscillated about zero.[28,30,40] The resultant acceleration signal was calculated as $\sqrt{x^2 + y^2 + z^2}$.[25,30,40]

Individual stance phases coinciding with force–plate contact were isolated from the tibia and low-back acceleration so that only stance phases performed at a constant speed were analyzed. Temporal alignment of the IMUs and force plates to identify the stance phases

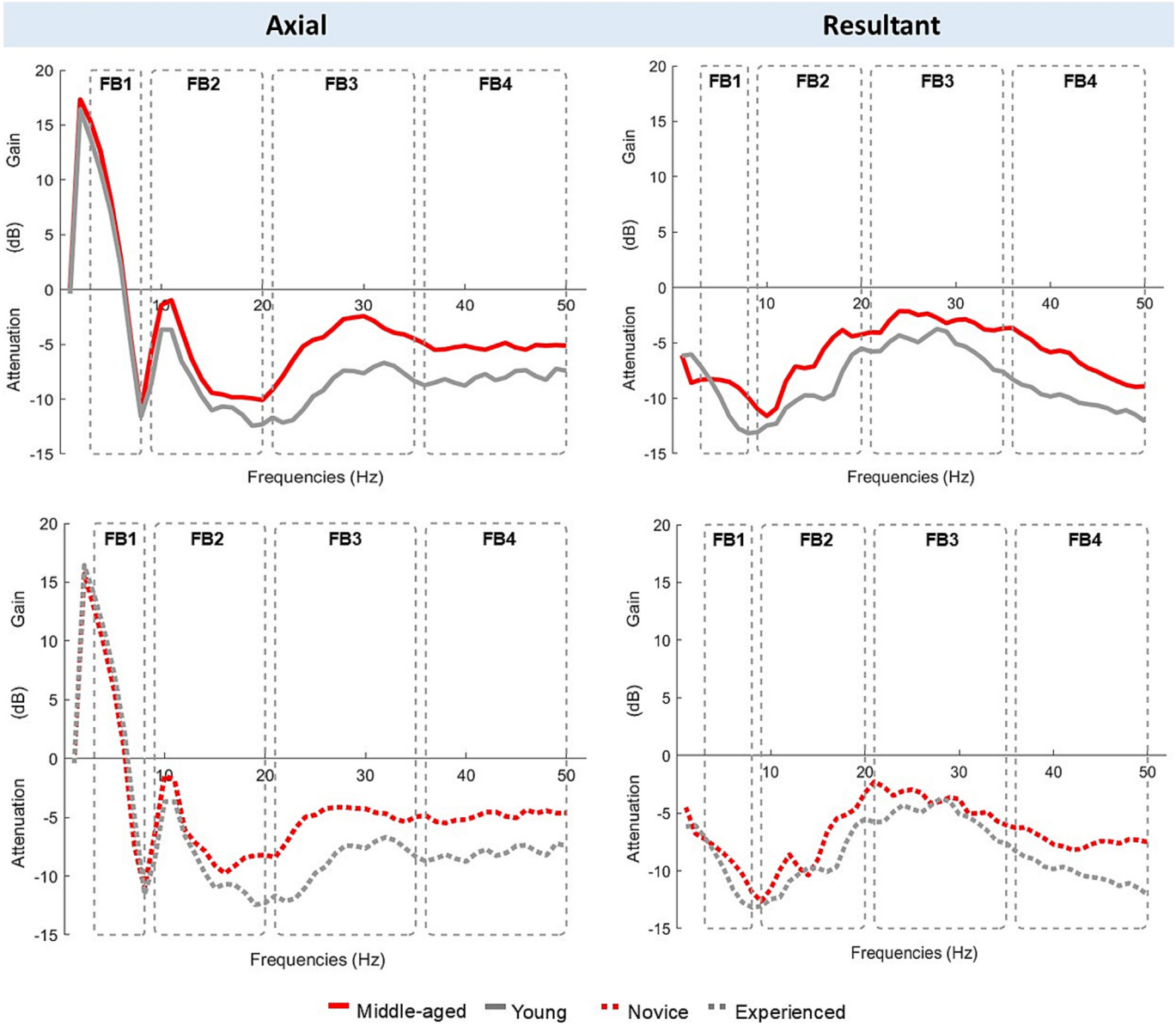


Fig. 1. Transfer function results for the axial (left column) and resultant (right column) shock attenuation of the young–experienced group (gray, solid and dashed lines), middle-age–experienced group (red, solid line), and young–novice group (red, dashed line). The area under each curve (i.e., integral) within 3–8 Hz (FB1), 9–20 Hz (FB2), 21–35 Hz (FB3), and 36–50 Hz (FB4) represents the degree of shock attenuated (negative values) or gained (positive values).

Table 1
Anthropometrics, demographics, and running training characteristics (mean ± 1 standard deviation) for each group. * indicates statistically significant at the 0.050 level; M: male, F: female. The age effects section compares the young–experienced runners with the middle-age–experience runners; the experience effects section compares the young–experienced runners with the young–novice runners.

Age effects	Young	Middle-aged	p-Value	Cohen's d
Age (years)	22.37 ± 4.09	52.95 ± 5.83	<0.001	6.16
Height (m)	1.71 ± 0.08	1.70 ± 0.07	0.65	0.13
Body mass (kg)	68.48 ± 10.03	68.64 ± 10.35	0.95	0.01
Sex distribution (n)	M = 15, F = 9	M = 8, F = 12	0.13	Chi sq: 2.21
Current km·week^{-1}	19.44 ± 10.71	27.23 ± 11.89	0.02*	0.69
Years running	7.42 ± 4.98	22.09 ± 13.40	<0.001*	1.50
Experience effects	**Experienced**	**Novice**	**p-Value**	**Cohen's d**
Age (years)	22.37 ± 4.09	22.50 ± 3.52	0.77	0.03
Height (m)	1.71 ± 0.08	1.75 ± 0.06	0.08	0.55
Body mass (kg)	68.48 ± 10.03	72.32 ± 8.35	0.21	0.40
Sex distribution (n)	M = 15, F = 9	M = 10, F = 4	0.57	Chi sq: 0.31
Current km·week^{-1}	19.44 ± 10.71	15.16 ± 5.02	0.10	0.47
Years running	7.42 ± 4.98	0.59 ± 0.36	<0.001*	1.70

coinciding with force–plate contact was completed following a previously published procedure.[30]

To calculate shock attenuation in the frequency-domain, the unfiltered, detrended, and bias-removed stance phases of the tibia and low-back acceleration signals were zero padded at both ends such that the signal length was a power of two, ensuring periodicity.[28] Signal power (i.e., energy) of the tibia and low-back accelerations was determined by computing the power spectral density (PSD) using a Hanning window. The PSD was normalized to 1 Hz bins.[24–26] The degree of shock attenuated between the tibia and low-back was calculated using the following transfer function[26]:

$$\text{Shock attenuation} = 10\log_{10}\left(\frac{PSD_{low\ -\ back}}{PSD_{tibia}}\right)$$

The integral of the transfer function output within FB1, FB2, FB3, and FB4 was calculated to assess the magnitude of shock attenuated (negative values) or gained (positive values) in decibels (Fig. 1). For each subject, the frequency-domain dependent variables were calculated for each limb as an average across eight trials.

2.4. Statistical analysis

Repeated measures *t*-tests with Bonferroni corrections revealed that shock attenuation within each frequency band was not significantly different between the right and left limbs of the participants ($p > 0.05$). Therefore, shock attenuation within each frequency band was averaged across the two limbs for each participant, yielding a single value per participant for each frequency band. This value was used in all primary and exploratory analyses.

Age and running experience were treated as categorical variables. The independent effects of age were assessed among the young and middle-aged–experienced groups. The independent effects of running experience were examined among young–novice and young–experienced groups. The young–experienced group was treated as the reference group for both comparisons. Unadjusted linear regression ($\alpha > 0.05$) assessed the independent effects of age and running experience on axial and resultant attenuation within each frequency bin. Separate models were used for each independent–dependent variable pair. Assumption violations were checked, and dependent variables were log-transformed when residuals deviated from normality per Q–Q plots.

Greater running exposure (current km·week^{-1} and running years; Table 1) in the middle-aged than the young–experienced groups may modulate the effects of age on shock attenuation. While this study was insufficiently powered to test for an interaction between age and experience, an exploratory analysis was performed to identify if adjusting for current running volume and years running in separate models altered the associations between age and shock attenuation (Supplemental material 1).

3. Results

Current km·week^{-1} and years spent running were significantly greater in the middle-aged–experienced versus the young–experienced group. The young–experienced group had run for more years than the young–novice group but no difference in km·week^{-1} was observed (Table 1).

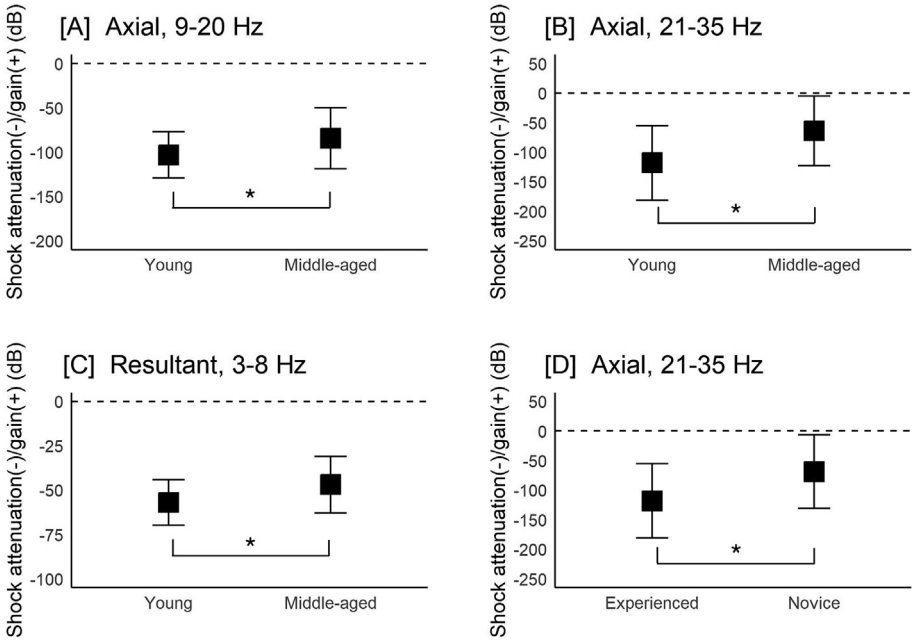


Fig. 2. Shock attenuation (y-axis) during running within the 3–8 Hz (FB1), 9–20 Hz (FB2), and 21–35 Hz (FB3) bands for comparisons that were significantly different between groups. Negative values indicate attenuation, while positive values indicate a gain in the impact shock signal propagated from the tibia to the low-back. *$p < 0.050$.

3.1. Age effects

The middle-aged–experienced group attenuated less axial shock within FB2 ($p = 0.01$, 95 % confidence interval (CI): 4.29–40.12, $\beta = 22.21$) and FB3 ($p = 0.002$, CI: 22.58–96.69, $\beta = 54.37$) compared with the young–experienced group (Fig. 2A and B; Supplemental material 2). The middle-aged–experienced group attenuated less resultant shock in FB1 than the young–experienced group ($p = 0.007$, CI: 3.20–20.03, $\beta = 11.62$) (Fig. 2C). No other associations were significant ($p > 0.050$) (Supplemental material 2).

The exploratory analysis revealed that adjusting for current weekly mileage resulted in middle-aged–experienced runners attenuating significantly less resultant shock in FB2 and FB3, and axial shock in FB4 — all of which were previously non-significant associations. Axial shock attenuation within FB4 was also significantly less in middle-aged–experienced runners than young–experienced runners after adjusting for current weekly mileage. Upon adjusting for the number of years spent running, the previously significant association of axial attenuation within FB2 with age was no longer statistically significant. However, the beta coefficient remained relatively unchanged in magnitude (unadjusted β: 22.21, adjusted β: 23.05) and direction (Supplementary material 1).

3.2. Running experience effects

The young–novice group attenuated less axial shock in FB3 than the young–experienced group ($p = 0.02$, CI: 6.72–92.13, $\beta = 49.43$) (Fig. 2D). No other associations with running experience and axial shock attenuation were significant ($p > 0.050$) (Supplemental material 1). Resultant shock attenuation was not significantly associated with running experience across frequency bins ($p > 0.050$) (Supplemental material 2).

4. Discussion

This study identified the associations of age and running experience with shock attenuation in the frequency-domain during overground running. Contrary to the hypothesis, the young–novice group relied less on passive attenuation mechanisms because they attenuated less axial shock between 21 and 35 Hz than the young–experienced group; axial shock between 3 and 8 Hz and 9–20 Hz and resultant shock attenuation across frequencies were not significantly different between experience groups. As hypothesized, the middle-aged–experienced group attenuated less resultant shock between 3 and 8 Hz, suggesting they use a different active attenuation strategy than young–experienced group. This and the other significant age-related associations were robust to differences in current weekly mileage and years spent running between the age groups, as seen in the exploratory analysis, suggesting age affects a runner's ability to attenuate shock independent of their running exposure. If shock attenuation is associated with RRIs, differences in active and passive shock attenuation between runners of varying ages and running experience levels may lead to differences in the type (e.g., soft versus rigid tissue) of RRI developed by each runner subgroup.

Contributions of fat, lean, and bone mass to impact-related energy absorption of specific frequencies are supported by animal models, computer simulation studies, and studies of humans.[13,41,42] For example, animal model studies showed that bone is a large contributor of high frequency attenuation (i.e., >18 Hz)[42] whereas absorption of shock vibrations between 10 and 50 Hz occurs by soft tissue in running humans.[44] Therefore, the relative contribution of fat, lean, and bone mass to passive high-frequency attenuation may change with running experience and age. Body fat percentage increases with age among athletes,[45] while lean and bone mass decrease.[46] However, as running training and experience increase, lean body mass[22] and bone mineral density[47] increase, whereas fat mass decreases with running training and improved diet.[48] These findings suggest the contribution of fat, lean, and bone mass to passive attenuation may change with running experience and that older or less experienced runners may have a greater potential to attenuate more high-frequency shock due to their greater fat mass than young–experienced runners. While the present study did not aim to specifically examine differences in passive shock attenuation mechanisms between groups, this study was part of a larger parent study for which body composition data was acquired from a smaller subset of participants who volunteered to undergo a dual x-ray absorptiometry scan. This subset included 38 out of the 44 participants used to test the effects of age and 27 out of the 38 participants used to test the effects of experience (Supplemental material 3). There were no significant differences in body composition measures (fat mass, fat-free mass, bone mineral density, and bone mineral content in the lower extremities) between this smaller sample of age and experience groups (Supplemental material 3). However, it is possible that differences in body composition may emerge with a larger sample size, given the large effect sizes in fat mass and bone mineral density between young–experienced and young–novice groups, for example.

Passive mechanisms are suggested to primarily attenuate the higher frequencies (>9 Hz) associated with impact,[28] but the position of the knee at impact may increase the relative contribution of active mechanisms to high-frequency attenuation and thereby decrease the contribution of passive mechanisms.[24] Given that peak knee flexion and knee flexion range of motion during stance decrease with age[19,29,35] and less running exposure,[18,20] active contributions to high-frequency axial attenuation may also decline with age and less running experience. Such hypothetical contributions of knee joint mechanics to high-frequency shock attenuation during running may explain why the young–novice and middle-aged–experienced groups attenuated less shock than young–experienced group, though the contribution of knee joint mechanics to attenuation of specific frequency ranges has yet to be examined during running. It is challenging to infer the contributions of active and passive shock attenuation to RRI risk until more evidence emerges regarding the degree to which musculoskeletal tissues and gait mechanics passively and actively contribute to shock attenuation during running.

Compared with the young–experienced groups, less high-frequency axial shock attenuation by the young–novice group could be explained by less axial tibial signal power (i.e., tibial shock). However, a supplemental analysis performed to test this hypothesis (Supplemental material 4) revealed that young–novice and young–experienced groups did not have different axial signal power at the tibia within 9–35 Hz, and thus comparable passive axial attenuation needs. This result was unexpected given that exposure to running may be related to shorter stride lengths and greater stride frequencies[49] and shorter stride lengths are associated with less axial tibial shock compared with longer stride lengths.[50] Therefore, stride parameters were either insufficiently different to drive differences in tibial shock between young–novice and young–experienced groups, or other gait differences between these groups negated the effects of stride parameters on tibial shock.

4.1. Limitations

The exploratory analysis in this study revealed that the effects of age on shock attenuation may not be influenced by running exposure. The sample size was insufficient to test for a combined effect of age and running experience on shock attenuation, but future work should explore these combined effects because participation in running for physical activity is increasing among middle-aged and older individuals.[51] Gait variables were not included in this study, but the gait of the novice and middle-aged populations may result in a unique shock attenuation response which reflects a different RRI risk than other runner populations like young–experienced runners.

5. Conclusions

Both middle-aged–experienced and young–novice groups attenuated less shock within 21–35 Hz than the young–experienced group, suggesting age and running exposure may influence the body's passive response to running-related impact shock among experienced and young runners, respectively. Age may affect a runner's ability to attenuate shock regardless of their running exposure. Consequently, both middle-aged runners who have been running and those who newly adopt running as a form of physical activity may need to be cognizant of shock attenuation demands from—and thereby potential injury risk to—musculoskeletal tissues which may differ from that of young–experienced runners.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2025.10.010.

CRediT authorship contribution statement

Gauri A. Desai: Study conceptualization, formal analysis, funding acquisition, investigation, methodology, visualization, validation, writing – original draft, writing – review and editing.
Molly Rosenberg: formal analysis, writing – review and editing.
Allison H. Gruber: Study conceptualization, methodology, investigation, project administration, resources, software, supervision, writing – review and editing.

Confirmation of ethical compliance

All testing procedures were approved by Indiana University Bloomington's Institutional Review Board, and all participants gave their written informed consent prior to participation.

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Declaration of interest statement

The authors have no competing interests to declare.

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Data availability

The data that support the findings of this study are available in the main manuscript text and the Supplementary materials. They are also available from the corresponding author upon request.

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