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ORIGINAL ARTICLE

John A. Mercer · Jason Vance · Alan Hreljac
Joseph Hamill

Relationship between shock attenuation and stride length during running at different velocities

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Abstract The purpose of the study was to investigate the characteristics of shock attenuation during high-speed running. Maximal running speed was identified for each subject [$n = 8$ males, 25 (SD 4.6) years; 80 (8.9) kg; 1.79 (0.06) m] as the highest speed that could be sustained for about 20 s on a treadmill. During testing, light-weight accelerometers were securely mounted to the surface of the distal antero-medial aspect of the leg and frontal aspect of the forehead. Subjects completed running conditions of 50, 60, 70, 80, 90, and 100% of their maximal speeds with each condition lasting about 20 s. Stride length, stride frequency, leg and head peak impact acceleration were recorded from the acceleration profiles. Shock attenuation was analyzed by extracting specific sections of the acceleration profiles and calculating the ratio of head to leg power spectral densities across the 10–20 Hz frequency range. Both stride length and stride frequency increased across speeds ($P < 0.05$) and were correlated with running speed (stride length $r = 0.92$, stride frequency $r = 0.89$). Shock attenuation increased about 20% per m·s^{-1} across speeds ($P < 0.05$), which was similar to the 17% increase in stride length per m·s^{-1}. Additionally, shock attenuation was correlated with stride length ($r = 0.71$) but only moderately correlated with stride frequency ($r = 0.40$) across speeds. It was concluded that shock attenuation increased linearly with running speed and running kinematic changes were characterized primarily by stride length changes. Furthermore, the change in shock attenuation was due to increased leg not head peak impact acceleration across running speeds.

Keywords Accelerometry · Impact · Stride length · Stride frequency

Introduction

With each foot strike during running, a shock wave is transmitted throughout the body, ultimately reaching the head (Shorten and Winslow 1992; Hamill et al. 1995; Derrick et al. 1998). The process of reducing the impact magnitude between the leg and head is shock attenuation. Movements (e.g., hip and knee flexion) play a major role in shock attenuation. For example, McMahon et al. (1987) investigated an extreme change in running kinematics referred to as Groucho running. By changing running kinematics, leg shock increased and attenuation of the impact increased compared to the normal running style. Understanding the relationship between running kinematics and shock attenuation is important, since running kinematics can change dependent on running conditions.

Although there are many variables used to describe running kinematics, the basic kinematic components are stride length and stride frequency. Derrick et al. (1998) reported that shock attenuation was affected by concurrent changes in stride length and stride frequency during running a set speed. For example, shock attenuation increased as stride length increased concurrent with a decreased stride frequency. Subsequent research has determined that shock attenuation is sensitive specifically to stride length changes (Mercer et al. 1999). This was determined by independently manipulating stride length and stride frequency and allowing running velocity to vary. It was observed that shock attenuation changed only when stride length changed. These

J.A. Mercer (✉) · J. Vance
University of Nevada, Las Vegas,
Department of Kinesiology, 4505 Maryland Parkway,
Box 453034, Las Vegas, NV 89154-3034, USA
E-mail: jmercer@nevada.edu
Fax: +1-702-8951500

A. Hreljac
University of California, Sacramento,
Department of Kinesiology and Health Science,
SLN 3002, 6000 J Street, Sacremento, CA 95819-6073, USA

J. Hamill
University of Massachusetts, Department of Exercise Science,
110 Totman, School of Public Health and Health Sciences,
University of Massachusetts, 30 Eastman Lane,
Amherst, MA 01003-9258, USA

experiments (Derrick et al. 1998; Mercer et al. 1999) required subjects to match a target stride length and it is currently not known if shock attenuation will vary with natural stride length changes.

Stride length will generally change as running velocity varies and it is known that shock attenuation increases linearly across running speeds of 2–5 m·s^{-1} (Shorten and Winslow 1992). The increased attenuation was hypothesized to be related in part to changes in running kinematics (Shorten and Winslow 1992). It may be that the change in running kinematics across these speeds was characterized by linear increases in stride length, since it has been reported that stride length increases linearly across submaximal speeds (Dillman 1975; Luhtanen and Komi 1978). Maximal running speeds, however, are generally achieved by increases in stride frequency not stride length (Dillman 1975; Luhtanen and Komi 1978). Presently there is no research on shock attenuation during maximal running speeds and it is not known if shock attenuation will continue to increase at maximal running speeds or if it will plateau as stride length plateaus.

The purpose of this study was to investigate the characteristics of shock attenuation across a range of running speeds up to an individual's maximal running speed. It was hypothesized that shock attenuation would be correlated with stride length changes across running speeds. A competing hypothesis was that shock attenuation would be correlated with stride frequency changes across the running speeds. Furthermore, it was hypothesized that stride length would increase in a non-linear fashion across speeds such that a plateau would be observed near maximal running speed.

Methods

Eight male subjects [age: 25 (SD 4.6) years; mass: 80 (8.9) kg; height: 1.79 (0.06 m)] volunteered for the study after giving informed consent approved by the university research council. All subjects were physically active and free from lower extremity injuries at the time of testing. They were all experienced in running on a treadmill and completed all running conditions on the same day.

Following a self-directed warm-up and familiarization period with the treadmill, maximal-running speed was determined. This was achieved by using the individual runner's knowledge and experimenting with different speeds. All subjects were encouraged to select the fastest speed they felt they could sustain for approximately 20 s. Several speeds were attempted by subjects with ample rest provided as needed between speed attempts. The highest speed that the subject could sustain was used as the maximal speed.

After identifying the maximal speed, lightweight accelerometers (PCB Piezotronics, Depew, N.Y.; model: 353C67) were mounted to the surface of the distal antero-medial aspect of the leg and anterior aspect of the forehead. The site for the leg accelerometer was selected due to the low amount of soft tissue in this anatomical region. Each accelerometer had a mass of 2 g, 100 mV g^{-1} sensitivity, and 0.3–12 kHz frequency range. The accelerometer secured on the leg was mounted to a small piece of balsa wood with the combined mass of the accelerometer and balsa wood being less than 4 g. The accelerometer and balsa wood mount was secured to the leg using an elastic Velcro strap. On the forehead, the accelerometer was secured to a rigid plastic headgear using a wax substance provided by the manufacturer for rigid securing of an accelerometer to a structure. All data were collected at 1,000 Hz for 20 s starting within 5–10 s upon attaining the test velocity. Twenty seconds was sufficient time to ensure that ten complete strides could be analyzed for all running conditions and all subjects.

After securing the accelerometers, subjects completed six running conditions that were based on a specified percentage of the runner's maximal running speed. The speeds tested corresponded to 50, 60, 70, 80, 90, and 100% of maximum speed. Rest between conditions was allowed as needed with order of speeds counterbalanced among subjects. The actual treadmill speed was calculated by using a magnetic switch that was triggered with each belt revolution.

Data reduction

The data analysis procedure consisted of analyzing the first ten consecutive strides within the 20-s data set for each subject per condition. Data were analyzed in the time and frequency domains. In the time domain, running speed was calculated using the treadmill-mounted magnetic switch while stride length and stride frequency were calculated using the leg acceleration profiles. Prior to all processing steps, head and leg acceleration profiles were smoothed using a low-pass fourth-order zero-lag Butterworth filter with a cutoff frequency of 100 Hz. Illustrated in Fig. 1 are typical leg and head acceleration profiles after smoothing. In the leg profile (Fig. 1b), there were distinct impact peaks while in the head profile (Fig. 1a) the impact peaks were attenuated considerably. Stride frequency was calculated as the time between consecutive leg impact peaks, with units of strides per second (Hz). Stride length was calculated by dividing treadmill speed (m·s^{-1}) by stride frequency (Hz). For each condition, mean stride length and frequency across ten strides was calculated for each subject and used for analysis. Leg and head peak impact accelerations were also recorded for the ten strides.

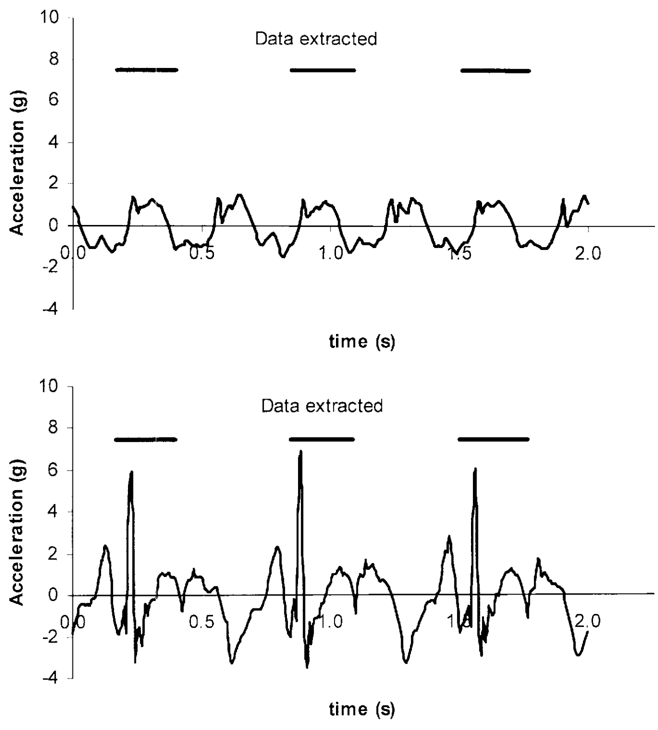

Fig. 1. Representative head (**a**) and leg (**b**) acceleration profiles during running. The *bars* represent the samples of data extracted for frequency analysis, with ten data sets extracted per subject per condition. **a** Representative head acceleration profile during running. **b** Representative leg acceleration profile during running

Power spectral densities (PSD) of ten repetitive patterns of leg and head accelerometer data were calculated via Fast Fourier Transformation for each subject–condition combination following procedures described by Shorten and Winslow (1992) and Derrick et al. (1998). Illustrated in Fig. 1 are horizontal bars representing example sections of data extracted from the accelerometer profiles used to calculate PSD. The mean and linear trends were removed from each section of data extracted from the acceleration profiles and each data set was padded with zeros to result in a total of 1,024 data points. Power spectral densities were calculated for head (PSD_{head}) and leg (PSD_{leg}) accelerometer profiles using a square window and adjusted to account for changes in power due to the zero-padding procedure. Finally, adjusted PSD were interpolated so each frequency bin was 1 Hz. These procedures follow the methods published elsewhere (Shorten and Winslow 1992; Derrick et al. 1998).

Shock attenuation was quantified by calculating the ratio of PSD_{head} to PSD_{leg} for each frequency within the 10–20 Hz frequency range. The ratios were then averaged across the frequencies to represent shock attenuation for that data set. A low ratio (i.e., closer to zero) between PSD_{head} and PSD_{leg} indicates greater attenuation of the impact magnitude compared to a high ratio.

Statistics

The dependent variables were stride length, stride frequency, shock attenuation, and leg and head peak impact accelerations with running speed as the independent variable. Repeated measures ANOVAs were used to test for differences in each dependent variable across speeds. Upon significant omnibus *F*-ratios, polynomial (first to fifth order) curve fitting follow-up testing was applied. Pearson correlation coefficient was calculated for combinations of shock attenuation, stride length, stride frequency, and running speed. SPSS version 10.1 was used to calculate all statistics.

Results

Table 1 illustrates means and standard deviations for running velocity, shock attenuation, stride length, stride frequency, head and leg peak impact accelerations. Stride length increased across speeds (Fig. 2, $P < 0.05$) with an overall increase of 53 (7.6)% across the 50–100% speeds ($p < 0.05$). Stride frequency also increased across speeds (Fig. 2, $P < 0.05$) with an overall increase of 30 (5.7)% across the 50–100% speed conditions. For both stride length and stride frequency there were significant first-, second- and fourth-order polynomials across speeds ($P < 0.05$). Stride length and running speed were strongly correlated ($r = 0.92$, $P < 0.05$) as were stride frequency and running speed ($r = 0.89$, $P < 0.05$).

Shock attenuation increased across speeds (Fig. 2, $P < 0.05$) with an overall increase of 55 (27.1)% across the 50–100% speed conditions. The high standard deviation was a result of one subject having no apparent change in shock attenuation across speeds. Of the other seven subjects, there was a 63 (15.2)% increase in shock attenuation. Although the single subject appeared to respond differently than the rest of the sample, the data for that subject were not eliminated from the statistical analysis. There was a significant linear trend of shock attenuation across speeds ($P < 0.05$), while no higher-order polynomials (i.e., second, third, fourth, fifth) were significant ($P > 0.05$). Shock attenuation was correlated with running speed ($r = 0.64$, $P < 0.05$) as well as with stride length ($r = 0.71$, $P < 0.05$) and stride frequency ($r = 0.40$, $P < 0.05$).

To further understand shock attenuation during running at different velocities, leg and head peak impact accelerations were analyzed. Leg impact accelerations increased on average 4.8 (2.3) g across the 50–100% speed conditions (Table 1, $P < 0.05$) while head impact accelerations increased only 0.5 (0.5) g (Table 1, $P < 0.05$). There were significant linear trends for both parameters across speeds ($P < 0.05$) and significant correlations between leg peak impact accelerations and running speed ($r = 0.81$, $P < 0.05$) and between head peak impact accelerations and running speed ($r = 0.48$, $P < 0.05$).

Discussion

The correlation ($r = 0.71$) between shock attenuation and stride length supports the hypothesis that these parameters would be related across speeds. It was expected that stride length would plateau near maximal running speed and therefore shock attenuation would plateau. However, neither stride length nor shock attenuation reached a plateau at the highest running speeds and the hypothesis that stride length would plateau was rejected. The competing hypothesis that shock attenuation would be related to stride frequency was also rejected because of the lower correlation ($r = 0.40$) between these parameters. However, the competing hypothesis was based on the expected plateau of stride length, which was not observed.

Table 1. Means and standard deviations for each variable across speeds equal to 10–100% maximal running speed

	Percent maximal speed					
	50%	60%	70%	80%	90%	100%
Shock attenuation	0.15 (0.05)	0.14 (0.05)	0.10 (0.05)	0.09 (0.04)	0.08 (0.04)	0.06 (0.03)
Stride length (m)	2.40 (0.17)	2.75 (0.22)	3.09 (0.23)	3.35 (0.25)	3.50 (0.22)	3.68 (0.18)
Stride frequency (Hz)	1.33 (0.06)	1.37 (0.09)	1.45 (0.10)	1.52 (0.13)	1.63 (0.12)	1.73 (0.14)
Velocity ($m \cdot s^{-1}$)	3.2 (0.3)	3.8 (0.3)	4.5 (0.4)	5.1 (0.4)	5.7 (0.5)	6.4 (0.5)
Leg (g)	6.1 (1.9)	6.1 (1.9)	7.2 (1.7)	7.9 (1.7)	10.0 (2.7)	10.9 (2.8)
Head (g)	1.4 (0.5)	1.5 (0.5)	1.6 (0.4)	1.7 (0.3)	1.9 (0.3)	1.9 (0.3)

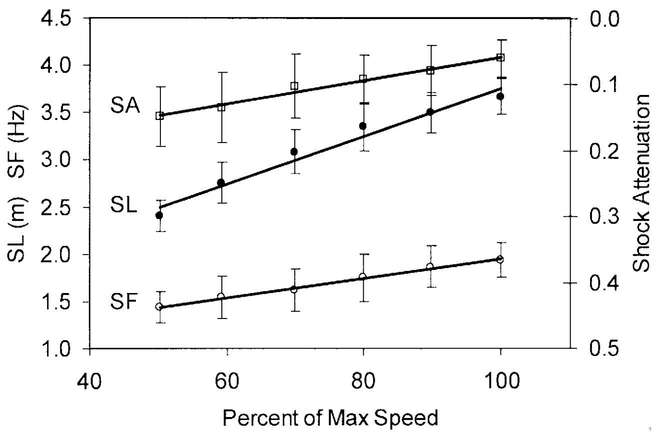

Fig. 2. Shock attenuation (*SA*), Stride length (*SL*) and stride frequency (*SF*) during running at different percent maximal running speeds. Each parameter increased linearly ($P < 0.05$) across speeds, with strong correlations between shock attenuation and speed ($r = 0.64$), stride length and running speed ($r = 0.92$) and stride frequency and running speed ($r = 0.89$). Shock attenuation was also correlated with stride length ($r = 0.71$) and stride frequency (r = 0.40). Each parameter illustrated is represented by the mean and standard deviation of eight subjects at each velocity along with the line of best fit

The observation of higher-order polynomials that fit the stride length-running speed relationship does support the hypothesis that stride length would increase in a non-linear fashion. These higher order polynomials are not evidence, however, for a plateau since stride length increased across all speeds and did not truly plateau (i.e., no change) at the higher speeds. Since treadmill speed was adjustable to only one tenth of a m·s^{-1} the actual speeds run were 50.2 (0.5)%, 59.3 (0.7)%, 70.0 (0.9)%, 79.9 (0.4)% and 89.8 (0.6)% of the highest running speed. Actual speed was tested for polynomial trends and it was determined that significant first-, second-, and fourth-order polynomials were present for actual speeds ($P < 0.05$). It is suggested that the non-linear change in stride length is partly explained by the non-linear change in actual speed and stride length did not plateau at higher speeds.

The lack of plateau of stride length at the maximal running speeds was not expected since it has been reported that maximal running speeds are achieved by primarily increases in stride frequency after maximal stride length was achieved (Dillman 1975; Luhtanen and Komi 1978). The lack of plateau of stride length may have been related to running on the treadmill compared to running overground. It has been reported that there are differences in lower extremity kinematics between treadmill and overground running (Frishberg 1983; Nigg et al. 1995). Elliott and Blanksby (1976) observed that stride length tended to be shorter during running at fast speeds (4.82–6.2 m·s^{-1}) on a treadmill versus overground. It may be that these kinematic differences between treadmill and overground running account for the lack of plateau of stride length at high speed running. Studies that have reported a lack of plateau of stride length at high speed running have used a treadmill (Knuttgen 1961; Sinning and Forsyth 1970; Chapman and Caldwell 1983). In contrast, Luhtanen and Komi's research (1978), in which a plateau of stride length was observed, was conducted using an indoor track. It may be that the strategy for increasing running speed is dependent on whether high speeds are achieved on a treadmill or overground. For example, during high speed treadmill running, it may be advantageous to continue to increase stride length since the treadmill belt is moving beneath the person. During overground running, however, the runner needs to propel himself or herself over the distance covered per stride length. Further research is needed to determine if shock attenuation during high-speed overground running is different than during treadmill running.

Whether or not stride length plateaus may be related to absolute maximum speed. The speed achieved by subjects in Luhtanen and Komi's (1978) study was greater (100%: 9.3 m·s^{-1}) than the highest speeds used by subjects in our study (100%: 6.4 m·s^{-1}). It may be that the limiting factor of achieving high absolute speeds is related to stride length, but in our study the highest speeds achieved were limited by some other factor. For example, subject fear of falling off the back of the treadmill or losing balance during running at high treadmill speeds may have been factors limiting individual speed choices. Another factor limiting subject choice of maximal speed may be experience with running at high treadmill speeds. Although subjects were experienced at running on a treadmill, their experience was typically related to running at submaximal speeds. It is not known if competitive runners experienced at running at high speeds may perform differently than recreational runners.

In our study, higher running speeds were accompanied primarily by changes in stride length with shock attenuation increasing in similar fashion as stride length. The 53% increase in stride length across the 50–100% speed conditions converts to about a 17% increase in stride length per 1 m·s^{-1} increase in speed. This is similar to other published data during running across similar speeds (Knuttgen 1961; Sinning and Forsyth 1970; Luhtanen and Komi 1978; Cavanagh and Kram 1990) as well as during walking at slower speeds (Voloshin 2000). Likewise, the correlation ($r = 0.92$) between stride length and running speed was similar to the correlation ($r = 0.99$) reported by Cavanagh and Kram (1990). The nearly 60% change in shock attenuation across speed conditions was similar to the 53% change in stride length, and a strong correlation between stride length and shock attenuation ($r = 0.71$) was observed. In contrast, there was only a moderate correlation ($r = 0.40$) between stride frequency and shock attenuation. The nearly 60% increase in shock attenuation across the 50–100% speed conditions results in a 20% shock attenuation increase per 1 m·s^{-1} increase in speed. Inspection of illustrations published by Shorten and Winslow (1992) indicates an increase of about 15% in shock attenuation for each 1 m·s^{-1} increase in speed, indicating similar changes in shock attenuation between studies.

Changes in shock attenuation can be explained mathematically by changes in the leg and/or head parameters. Figure 3 illustrates the leg and head peak impact accelerations in the time domain. It is clear that the changes in shock attenuation are due to changes in leg and not head peak impact acceleration. The increase in leg accelerations was about 42% increase per 1 m·s^{-1} increase in running speed. This value is similar to 34% increase in leg accelerations per m·s^{-1} reported by Clarke et al. (1985). Even though peak head impact acceleration did increase with running speeds, the 0.5 g increase between the 50% and 100% speed conditions was small relative to the mean 4.8 g increase in leg peak impact acceleration. Hamill et al. (1995) suggested that a relatively constant head acceleration was necessary to maintain a stable visual field during submaximal running speeds. It appears that this may also be the case in high-speed running.

Although head peak impact acceleration remained within a narrow range of magnitude, it does not seem that runners selected a running style that purposely optimized shock attenuation across speeds to maintain head peak impact magnitudes. Derrick et al. (1998) reported that when running at a set speed, shock attenuation decreased as stride length decreased, since leg shock decreased concurrently. During some speeds, runners could elect to use a short stride length (and high stride frequency) in order to reduce the leg shock. In the present study, however, this was not the case since stride length increased across speeds as did leg shock. Nevertheless, despite large increases in leg shock across speeds, magnitude of head peak impact remained within a narrow range of magnitude. What is not presently known is whether the amount of energy absorbed through passive structures (e.g., bone) changes across running speeds. It may be that different energy absorbing structures are stressed to a different extent at different running speeds resulting in nearly constant head peak impact acceleration.

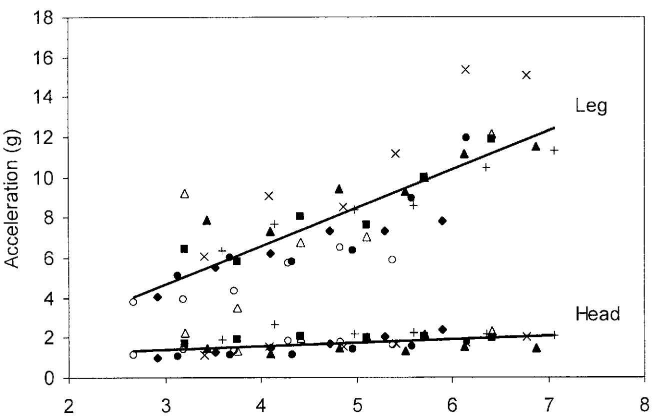

Fig. 3. Head and leg peak impact accelerations during running at different speeds for all subjects. Each subject is represented by unique markers along with a line of best fit for the entire data set. Both parameters increased linearly across speeds ($P < 0.05$) with leg peak impact accelerations increasing on average 4.8 g compared to a small 0.5 g increase in head peak impact accelerations

Ideally, the sensitive axes of the two accelerometers were aligned during all conditions. Since stride length changed by over 50% across speeds, the sensitive axes of the two accelerometers may not have been aligned. However, Derrick et al. (1998) reported that the leg angle (relative to vertical) was 8.1° during stride length conditions that were 20% longer and 7.9°during stride length that were 20% shorter than the preferred stride length. Nevertheless, future studies may benefit by using accelerometers that are also sensitive to the perpendicular direction relative to the tibia. Since the shock wave resulting from the foot-ground collision is propagated in all directions within a runner's body, our understanding of shock attenuation may benefit by determining the effect of changes in orientation of accelerometer axes on leg and head shock.

Conclusion

As speed increased, changes in running kinematics were characterized primarily by changes in stride length. Furthermore, the changes in shock attenuation across running speeds were similar to the changes in stride length with no plateau of either stride length or shock attenuation observed during the speeds tested. Across the speeds tested, impact magnitudes were attenuated despite the large increases in speed and impact magnitudes. Changes in shock attenuation across speeds were characterized by increases in leg impact acceleration concurrent with peak impact acceleration recorded at the head remaining within a narrow range of magnitude. Across the speeds tested, it is concluded that shock attenuation is related to natural changes in stride length.

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