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Segment Coordination Variability Differs by Years of Running Experience

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Abstract

Running is a popular activity that results in high rates of overuse injury, with less-experienced runners becoming injured at higher rates than their more-experienced peers. Although measures of joint kinematics and kinetics and ground reaction forces have been associated with overuse running injuries, similar differences across levels of running experience have not been found. Because running is a motor skill that may develop with experience, an analysis of segment coordination and its variability could provide additional insight into why injury incidence decreases with increasing experience.

Purpose: The purpose of this study was to determine if less-experienced runners have different segment coordination and lower segment coordination variability compared with their more-experienced peers.

Methods: This retrospective analysis included 20 more-experienced (≥10 yr running) and 21 less-experienced (≤2 yr running) runners. Sagittal thigh versus shank and shank versus foot segment coordination and coordination variability were calculated using a modified vector coding approach as individuals ran on a treadmill at preferred pace. Coordination and its variability were compared between groups during terminal swing and early, mid, and late stance for both segment couples.

Results: Segment coordination was similar between less- and more-experienced runners. Less-experienced runners had lower segment coordination variability compared with more-experienced runners for both the thigh versus shank and shank versus foot couples. This lower variability occurred during early and mid stance.

Conclusions: Runners appeared to attain stable segment coordination patterns within 2 yr of consistent running, but had lower coordination variability compared with individuals who had

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been running for 10 or more years. These results suggest that assessment of movement patterns and their flexibility may help inform injury prevention or treatment strategies for less-experienced runners.

Keywords

VECTOR CODING; RUNNING INJURY; BIOMECHANICS; MOTOR CONTROL

Running provides many health benefits, but the incidence of overuse injuries among runners is high (1,2), particularly for novice or less-experienced runners (3–5). Investigations as to how less-experienced runners differ from their more-experienced peers often focus on specific biomechanical measures associated with overuse injuries (e.g., peak hip adduction angle and vertical ground reaction force loading rate). However, these studies generally find no differences in running biomechanics regardless of experience level (6,7), suggesting that other factors may predispose less-experienced runners to injury. Because running is a motor task, motor control strategy may develop over time and coordination patterns and coordination variability may differ by experience level. In terms of injury risk, more years of running experience may allow for the development of coordination patterns that reduce the accumulated load on musculoskeletal tissues and allow for flexibility of movements under varying task demands. Thus, an examination of movement organization and flexibility via coordination analysis may provide insights about potential contributors to the higher incidence of injury in less-experienced runners.

Coordination and coordination variability describe the organization and flexibility of a movement pattern. *Coordination* describes the organization of redundant degrees of freedom (e.g., multiple muscles, joints, and joint rotations that could be used to accomplish a task) into a control unit. Because of the redundancy in the musculoskeletal and neuromotor systems, different coordination patterns or slight variations in a coordination pattern could be used to accomplish the same task, resulting in *coordination variability* (8–10). As individuals gain expertise with a motor skill, they may develop a coordination pattern that optimizes task performance and retain a degree of variability that allows them to respond to changing environmental demands or internal constraints. A secondary benefit of this increased variability is the distribution of loading across musculoskeletal tissues or reduced accumulated loading to a particular tissue, which can be protective against overuse injury.

Altered coordination patterns are evident in skill acquisition of a single action (11–15) as well as cyclic movement tasks, such as swimming (16). Coordination variability also changes with skill acquisition or experience, but the direction of change varies among methods used and cohorts examined (17). In studies of race walking (18), cycling (19), and gymnastics (14), continuous relative phase (CRP) variability, which is a measure of the phasing of joint or segment angular velocities and angular positions, was lower in trained athletes or those of higher competitive level compared with untrained or lower-skilled individuals. In a study comparing competitive to infrequent runners, CRP variability was not different between groups (20). In contrast to results obtained using CRP, segment coordination variability appears to decrease with task novelty. In an acute intervention study, experienced runners had a decrease in segment coordination variability in response to running at a novel cadence (21). As segment coordination and coordination variability are calculated directly from segment orientations, differences across experience level could be relevant to overuse injury risk, as the orientation of segments relative to each other and to gravity influences both internal and external loads on the musculoskeletal system.

The hypothesis that coordination and its variability would influence the incidence of overuse joint injuries is supported in the literature as coordination, and coordination variability have been found to differ between uninjured runners and runners with patellofemoral pain (22–25) and low back pain (26). These findings suggest that injury-resistant runners, as opposed to injury-prone runners, may have developed coordination patterns that do not exceed musculoskeletal tissue tolerances. For less-experienced runners, poor coordination patterns that result in high loads combined with weaker or less-adaptable tissues may contribute to heightened injury rates despite fewer accumulated miles or loading cycles. Similarly, injury-prone runners may have either too much or too little coordination variability, potentially resulting in intermittent high loads that have to be resisted by poorly conditioned tissues or, conversely, consistent loads concentrated on a small area of tissue. Differing coordination in less-experienced runners could lead to higher risk of injury, as some overuse injuries have been associated with altered coordination and lower coordination variability. Thus, the purpose of the current study was to determine if segment coordination and segment coordination variability differed between less-experienced (≤2 yr consistent running) and more-experienced (≥10 yr consistent running) runners. We hypothesized that less-experienced runners would have thigh–shank and shank–foot coordination patterns that differed from more-experienced runners, and that less-experienced runners would have lower coordination variability in these lower extremity segment couples compared with more-experienced runners.

METHODS

This study was a retrospective analysis of data previously collected in our laboratory (6), in which all participants provided written informed consent as approved by the Institutional Review Board at the University of Michigan before completing any study procedures. Runners were recruited from the community via flyers and outreach to local running clubs and running stores. Participants for the current study included males and females who reported running consistently (≥12 miles per week for at least 6 months of the year) for no more than 2 yr *or* for 10 or more years. All individuals were injury free in the 6 months before their data collection, used no prosthetic or orthotic devices, and reported being comfortable running on a treadmill. Characteristics for the runners included in this analysis are provided (Table 1).

Kinematics were collected at 200 Hz using inertial measurement units (IMUs; Myomotion, Noraxon, Scottsdale, AZ) as participants ran at self-selected comfortable training pace on a pressure-sensing treadmill. All participants ran in their own training shoes. Foot strike and toe-off were determined as the times when vertical ground reaction force (as calculated from treadmill pressure) exceeded and fell below 5 N. Standard placement of IMUs was used across all participants for the left thigh (halfway along segment length on lateral aspect), shank (halfway along segment length on lateral aspect, aligned anterior/posterior with thigh

IMU), and foot (dorsal aspect of shoe) in accordance with recommendations from the sensor manufacturer (Myomotion). Immediately before data collection, IMU alignment was calibrated to anatomical alignment during a static standing trial. IMU segment orientations were calculated using built-in algorithms and filtering of Noraxon Myomotion software (v 3.8) using the “Treadmill Mode” setting to anchor running direction and correct for drift of sensor orientation estimates.

For each participant, sagittal plane segment angles were extracted and normalized to 101 points per gait cycle for 50 consecutive strides of data. Fifty strides of data were used as this provided stable estimates of coordination variability (27). Segment coordination and its variability were calculated for sagittal plane thigh versus shank and shank versus foot couples. Sagittal plane segment couples were selected for analysis because IMU orientation excursion estimates have been shown to be most accurate for large sagittal-plane excursions (28), and previous studies examining injury or novel tasks in running identified differences in sagittal plane movement (21,23).

Coordination and coordination variability were calculated using a modified vector coding technique (29,30). Briefly, for each segment couple and between every time step in the gait cycle, the coordination phase angle was calculated as the angle of the vector connecting consecutive gait cycle points of the distal versus proximal segment angle-angle plot with respect to the right horizontal using the four-quadrant inverse tangent. This produced phase angles between 0° and 360° for the 100 time steps between the 101 normalized gait cycle points for each segment couple. Coordination variability was calculated as the circular standard deviation of the phase angle at each time step across the 50 strides of data. For each participant, coordination data were averaged during early, mid, and late (thirds of) stance, and terminal swing (last 15% of swing), using a circular average for phase angles and a linear average for coordination variability. A schematic of the vector coding calculations and the definitions corresponding to different phase angle values are provided (Fig. 1). Coordination data were compared between groups for each gait cycle phase and segment couple using circular one-way ANOVA (Watson–Williams test) for segment coordination phase angles with $\alpha = 0.05$. As variability is often nonnormally distributed, coordination variability was compared between groups for each gait cycle phase using bootstrap for 95% confidence intervals (CI) and one-sided permutation tests for significance, with both tests using 1000 samples (R version 3.4.2). Effect sizes (ES) were also calculated where variability outcomes were significantly different.

RESULTS

Less- and more-experienced runners had different phase angles during terminal swing and early stance for the shank versus foot couple (48.7°; [SD 3.9°] vs 52.6°; [SD 6.6]; $P = 0.03$; ES, 0.72; 198.2°; [SD 2.5°] vs 203.9°; [SD 4.2]; $P < 0.001$ ES, 1.65; Fig. 2). However, these differences did not result in a significant group difference in coordination pattern, as both less- and more-experienced runners were in-phase during both early stance and terminal swing. Less-experienced runners had significantly lower coordination variability compared with more-experienced runners for the thigh versus shank and shank versus foot couples during early (6.3°; CI, 5.5°–7.1° vs 9.6°; CI, 7.1–12.1; $P < 0.001$; ES, 1.04; 5.5°; CI, 3.7°–

7.3° vs 10.9°; CI, 6.8–15; $P = 0.003$; ES, 1.17) and mid stance (3.0°; CI, 2.6°–3.4° vs 5.4°; CI, 2.6–8.2; $P = 0.004$; ES, 3.39; 3.0°; CI, 2.6°–3.4° vs 6.2°; CI, 3.1–9.3; $P = 0.007$; ES, 2.65; Fig. 3).

DISCUSSION

In this study, we quantified differences in segment coordination and segment coordination variability by experience level that could help explain the higher rates of injury in less-experienced runners. We examined sagittal plane coordination and variability for the thigh versus shank and the shank versus foot with the hypotheses that less-experienced runners would have different sagittal plane coordination and lower coordination variability across the knee and ankle compared with more-experienced runners. In partial support of our hypotheses, less-experienced runners had lower coordination variability for the thigh versus shank and shank versus foot during early and mid stance. Coordination phase angles were similar between groups for both segment couples and across all gait cycle phases.

To our knowledge, only one other study has investigated the influence of running experience on coordination and its variability (20), and those authors found no difference in coordination variability by experience level. The difference in results from our current study may be due to the way in which runners were grouped. Floria et al. (20) used training volume (days and miles run per week) to quantify experience. The present study used years of running to quantify experience. Participants in the current study also had to run at least 6 months per year, and actually reported running more than 10 months per year in both groups. This method ensured that runners were performing the movement pattern on a regular basis throughout years of running.

The similarity in sagittal thigh versus shank and sagittal shank versus foot coordination between less- and more-experienced runners suggests that consistent lower extremity movement patterns (i.e., general form) develop within 2 yr of running. The significant but small group differences in in-phase coordination around foot strike may suggest that at some point in running form development coordination patterns change, but this cross-sectional analysis cannot determine if this is truly the case. However, the lower coordination variability during early and mid stance for less-experienced runners indicated that repetitive practice or experiential learning may be needed to develop motor flexibility, particularly for the aspect of movement that requires stability against impact and gravitational forces. Lower segment coordination variability in the less-experienced group could influence a runner's ability to appropriately absorb the impact of early stance and properly activate musculature to support body against gravity during mid stance. This may accentuate injury risk as relatively higher rates of loading in early stance have been associated with many injuries (31). Additionally, lower coordination variability may increase the cumulative loading to injury-susceptible structures by repetitive loading being applied to a small area of tissue. Peak patellofemoral loading rates and peak patellofemoral force occur during early and mid stance (32), and low coordination variability during these times could result in these high rates and forces being absorbed by a reduced area of patellofemoral structures. Lower coordination variability has been reported in runners with patellofemoral pain (22,23) compared with asymptomatic controls. Those findings corroborated epidemiologic studies that reported higher rates of knee injuries in novice runners compared with the other groups (33).

Our finding of similar coordination patterns across experience levels differs from some previous comparisons of athletes who differed by training or performance level. Novice versus expert gymnasts executing a longswing (14) and recreational versus competitive breaststroke swimmers (16) displayed group differences in CRP coordination between upper- and lower-body joints. Further, some novice gymnasts showed changes in coordination patterns as a result of practice—albeit in a way that made them less similar to experts (14)—suggesting that training or skill can impact coordination. A possible explanation for differences between the present study results and those of coordination in other sports is that we only inquired about consistent running experience, not skill development specifically. Coordination patterns may differ between runners who practice or train their running form versus those who just run. Similarly, individuals who have been running for a longer time may have accumulated more mileage on varied terrain or at varied speeds, potentially acquiring more flexibility in running movement patterns in the process.

Differences in coordination by training volume have also been reported in runners, with a study of higher versus lower mileage groups (33.8 vs 7.2 miles per week) finding group differences in the coordination of transverse and frontal plane hip and knee motions (34). Our results indicated that, even in groups with the same average training volume and running speed, years of experience performing a task (i.e., running) may lead to increased movement flexibility. Additionally, although the more-experienced runners in this study trended toward being older than the less-experienced runners (Table 1), age itself may not be a factor driving group differences in coordination variability [(35); see Table, Supplemental Digital Content 1, Coordination and coordination variability analysis for age 20–39 groups subset, http://links.lww.com/MSS/B505]. The runners in our study had a wide range of training volumes, but the groups did not differ on average for weekly mileage or preferred running pace. Although a similar training/experience comparison is not available from other sport literature, our results suggest that in individuals who regularly participate in a sport, training volume or skill level has a larger impact on coordination than years of sport experience.

This study, however, has limitations. As with many studies of coordination and coordination variability, data in the current study were collected as individuals ran on a treadmill. Although all participants were familiar and comfortable with running on a treadmill, the treadmill may have imposed constraints that altered coordination from that of overground running. As both groups ran on the same treadmill at their own preferred speed, however, this constraint would have minimal effect on between-group differences. In addition, we divided our runners' experience levels based on years of running. There are many ways to quantify experience level, including accumulated training, experience with competition, and performance level. We chose our definition of experience because it provided a clear demarcation in historic running exposure with minimal influence of an individuals' ability to recall training volumes over long periods of time and because of the availability of information in this retrospective analysis. Further, our definition of experience level may have introduced an age bias into our data set. Although our group ages were not significantly different and previous research has not found a difference in coordination variability by age (35), we did not specifically address the effect of age in this study. Finally, due to the cross-sectional study design, we are unable to comment on whether more-experienced runners developed greater coordination variability over time or whether they inherently possessed this coordination variability, thus allowing them to stay sufficiently healthy to continue to run consistently for more than a decade. Longitudinal studies are needed to document the natural history of motor pattern acquisition in running for adults.

Overall, less- and more-experienced runners did not have different movement patterns about the knee and ankle, but less-experienced runners produced these patterns with less movement flexibility. This lower motor control flexibility in combination with the high loads that occur during running may contribute to the higher rates of injury in less-experienced runners compared with more-experienced runners. The current results reveal new insights that may be useful for developing methods to assess potential injury risk, monitor the effectiveness of training strategies aimed at developing and refining motor skill and flexibility with regard to running or developing running schedules that limit cumulative loading on not-yet-adapted tissue.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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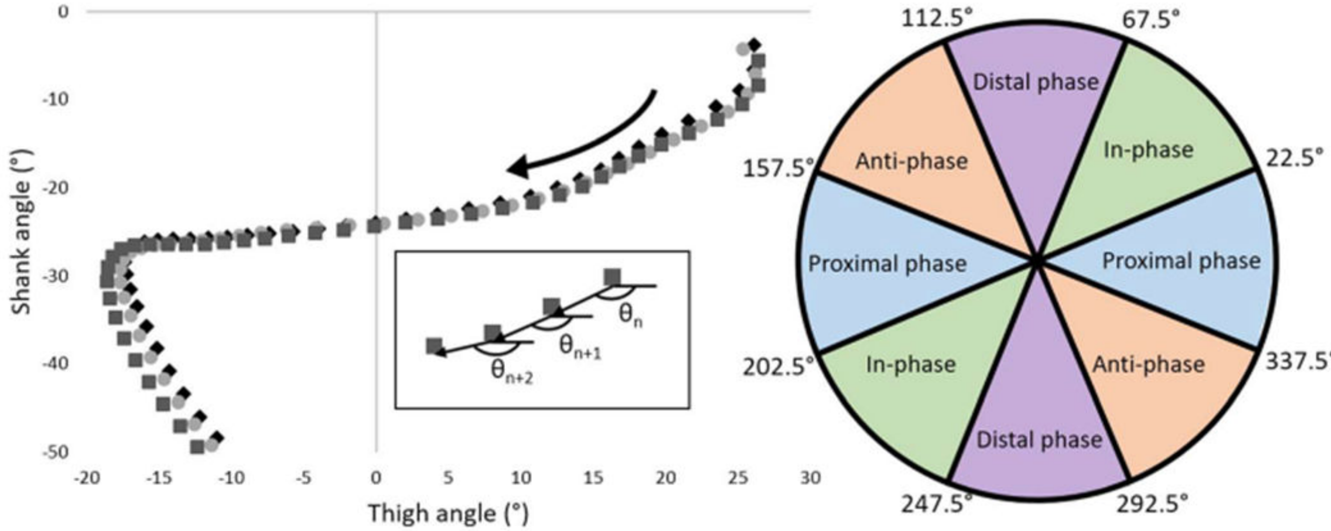

FIGURE 1—.

Exemplar vector coding methods. Left-hand graph shows a sagittal thigh vs shank angle-angle plot during stance over multiple strides. *Curved arrow* indicates direction of gait cycle progression. Inset demonstrates phase angle (θ) calculation between gait cycle points. Right hand graph shows angle ranges for phase angle patterns. The phase angles exemplified in the inset would fall into the 157.5° to 202.5° proximal phase pattern.

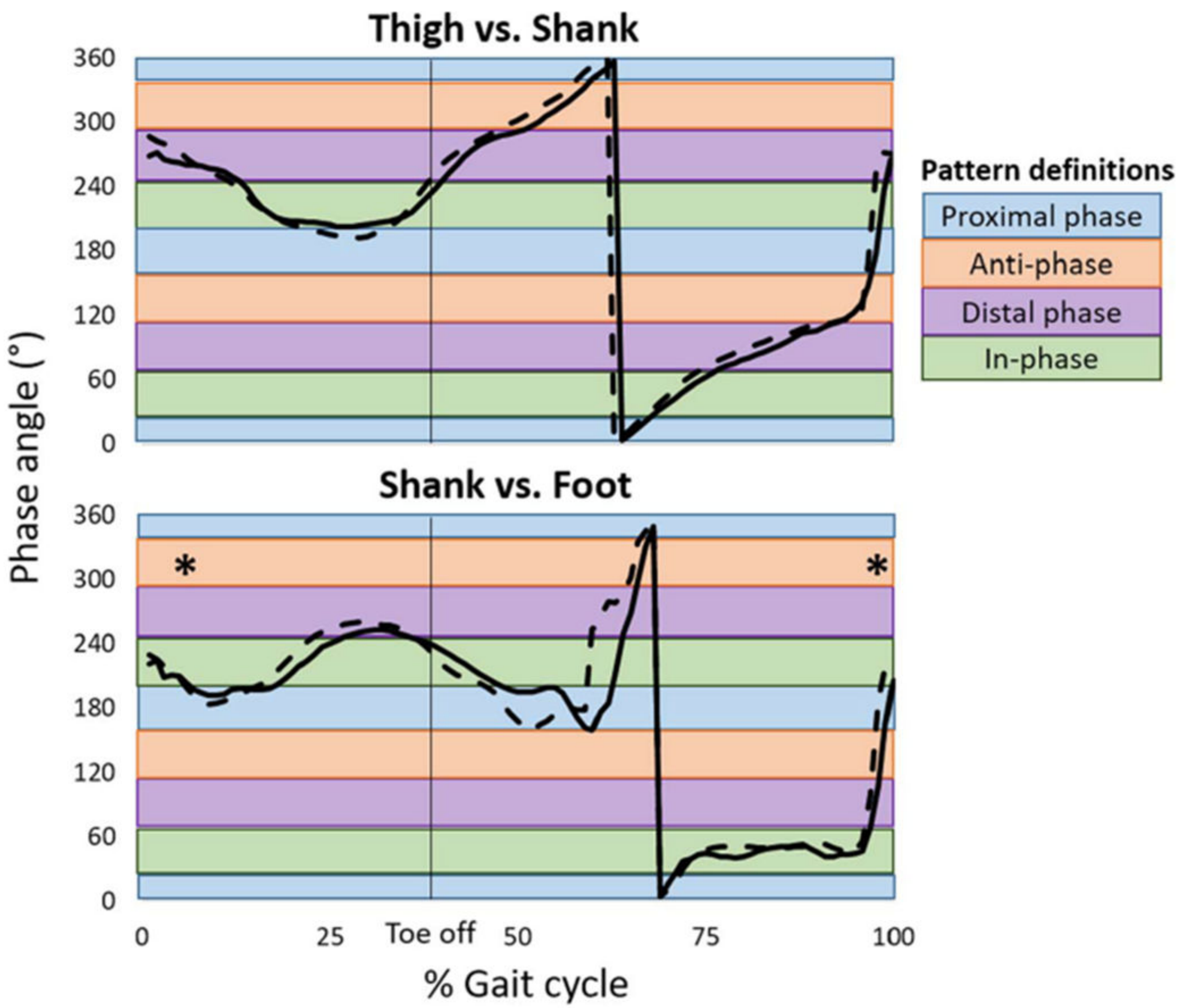

FIGURE 2—.

Comparison of segment coordination between less-experienced runners (*dashed lines*) and more-experienced runners (*solid lines*). *Significant difference between groups during terminal swing and early stance for the shank vs foot couple. Although there were these significant group differences, coordination pattern (color + key) did not differ between groups.

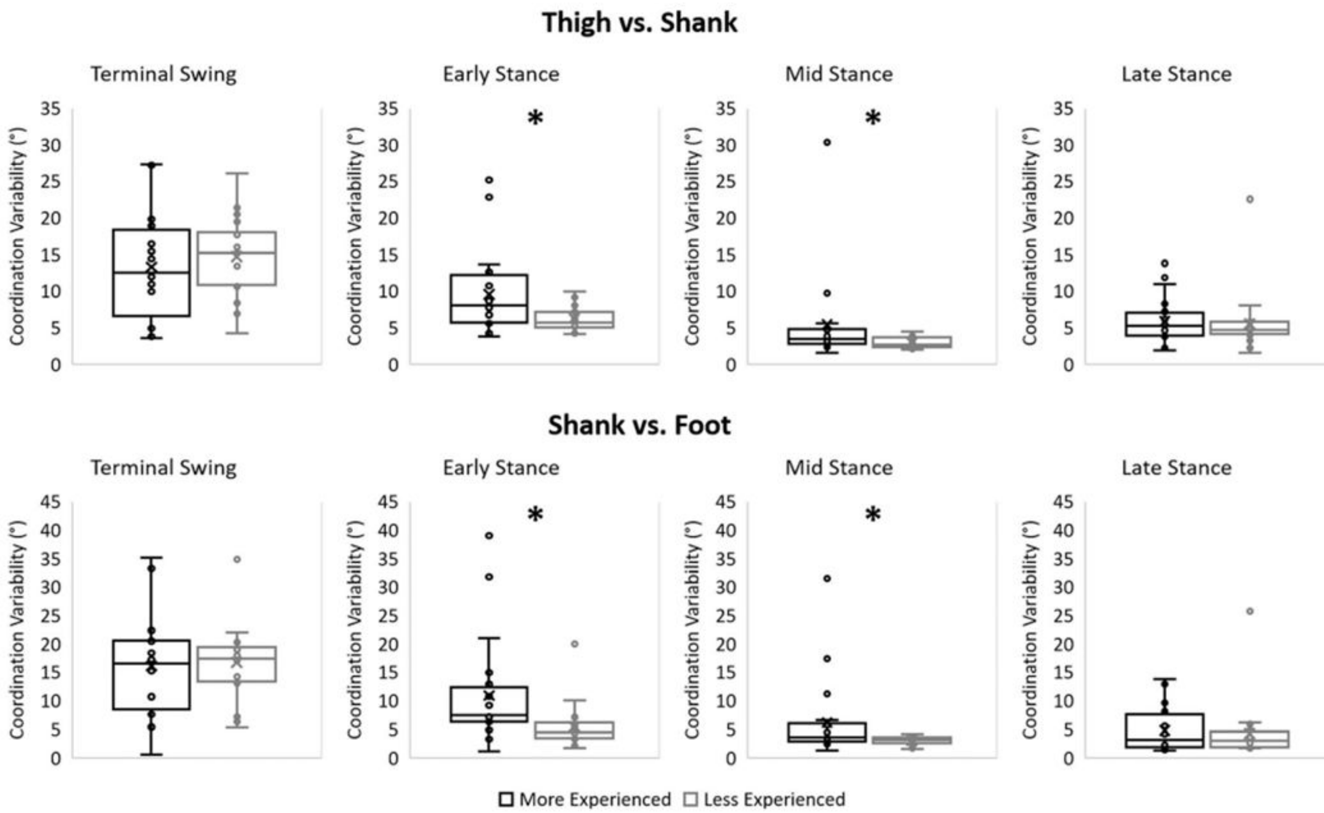

FIGURE 3—.
Comparison of segment coordination variability between less-experienced runners (*black box and whiskers*) and more-experienced runners (*gray box and whiskers*) for gait cycle phases of interest. Circles indicate individual data points. *Significant difference between groups.

TABLE 1.

Characteristics of more- and less-experienced runners [mean (SD)].

	More Experienced	Less Experienced	*P*
n	20 (16 male)	21 (17 male)	—
Running years	15.8 (8.3)	1.3 (0.7)	<0.01
Running speed ($m \cdot s^{-1}$)	3.2 (0.3)	3.2 (0.4)	0.62
Age (yr)	38.2 (10.9)	32.3 (9.4)	0.07
BMI ($kg \cdot m^{-2}$)	22.1 (1.9)	23.6 (3.0)	0.06
Typical weekly mileage (miles)	34.3 (15.9)	25.5 (15.4)	0.08
Typical months run per year	11.4 (1.2)	10.4 (2.6)	0.10

Running experience was determined by asking the participants how many years they consistently ran at least 12 mile·wk^{-1} for at least 6 months of the year.