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Differences in lower-limb coordination and coordination variability between novice and experienced runners during a prolonged treadmill run at anaerobic threshold speed

Shiwei Mo, Daniel H.K. Chow*

Department of Health and Physical Education, The Education University of Hong Kong, Hong Kong SAR

* Corresponding author. Address: 10 Lo Ping Road, Tai Po, New Terries, Hong Kong SAR. Tel: +852 2948 6421. E-mail address: danielchow@eduhk.hk (D.H.K. Chow)

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Conflict of Interest

The authors declare that they have no conflict of interest.

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Abstract

This study investigated differences in lower-limb coordination and coordination variability between experienced and novice runners during a prolonged run. Thirty-four participants were categorised as either experienced (n=17) or novice runners (n=17). All participants performed a 31-min treadmill run at their individual anaerobic threshold speed, and lower-limb kinematic data were acquired in the sagittal plane at the beginning, middle, and end of the run. Lower-limb coordination and variability during the stance phase were quantified using a vector coding technique for hip-knee, knee-ankle, pelvis-thigh, thigh-shank, and shank-foot couplings. Repeated-measure analysis of covariance revealed that running experience and time had significant interactions on the coordination patterns for hip-knee and pelvis-thigh couplings. During the midstance, experienced runners exhibited a higher percentage of in-phase motion for pelvis-thigh and knee-ankle couplings while novice runners displayed a higher percentage of distal motion for pelvis-thigh coupling and anti-phase motion for hip-knee coupling. Experienced runners displayed more variability in hip-knee and shank-foot couplings, and novice runners had more variability in hip, knee, and thigh motion. Experienced and novice runners adapted to progressive fatigue through different lower-limb coordination patterns. Throughout the prolonged run, experienced runners demonstrated greater coordination variability and novice runners displayed greater joint and segment variability.

Keywords: coordination; coordination variability; running experience; fatigue; anaerobic threshold speed

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Introduction

Running is a popular physical activity, but the reported incidence of lower-limb injuries is up to 79% (van Gent et al., 2007). Although numerous studies have investigated running mechanics (Agresta, Peacock, Housner, Zernicke, & Zendler, 2018; Noehren, Hamill, & Davis, 2013; Schmitz, Russo, Edwards, & Noehren, 2014), the relationship between running mechanics and running-related injuries remains unclear (Ferber, Hreljac, & Kendall, 2009). The coordination between segments and joints during running has been studied in injured individuals using dynamical systems theory (Brown, Zifchock, Hillstrom, Song, & Tucker, 2016; Hamill, van Emmerik, Heiderscheit, & Li, 1999; Heiderscheit, Hamill, & van Emmerik, 2002; Miller, Meardon, Derrick, & Gillette, 2008), and its association with running-related injuries was identified (DeLeo, Dierks, Ferber, & Davis, 2004). Coordination is a goal-directed behaviour and refers to the individualised manner in which performer satisfies specific constraints during task execution (Davids, Glazier, Araújo, & Bartlett, 2003). Lower-limb coordination in healthy individuals has been studied (Boyer, Freedman Silvernail, & Hamill, 2014; Dierks & Davis, 2007; Floría, Sánchez-Sixto, Ferber, & Harrison, 2018; Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016), but the coordination patterns in runners of different degrees of experience that are exhibited during a prolonged run are unknown.

Variability of lower-limb coordination reflects the flexibility of the locomotor system adapting to ever-changing constraints that arise from environmental or physiological changes (Davids et al., 2003; Hafer, Brown, & Boyer, 2017; Heiderscheit et al., 2002; Hein et al., 2012; Lilley, Herb, Hart, & Hertel, 2018; Miller et al., 2008). Research has ascertained a link between coordination variability (CV) and running-related injuries (Bartlett, Wheat, & Robins, 2007; Hamill, Palmer, & van Emmerik, 2012), and many studies have reported that injured groups (individuals exhibiting symptoms of patellofemoral pain, or iliotibial band syndrome, or other injuries) typically exhibited lower CV than healthy control groups (Hamill et al., 1999;

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Heiderscheit et al., 2002; Lilley et al., 2018; Miller et al., 2008). CV was even identified as a measurement for distinguishing between injured and healthy runners (Hein et al., 2012). High CV may distribute loading over a broad area of tissue and thereby reduce the risk of running-related injury (Bartlett et al., 2007; Hamill et al., 2012). However, excessively high coordination variability may be also indicative of an injured individual (Hamill et al., 2012) and detrimental in running performance (Davids et al., 2003). Researchers contend that an optimal window of CV exists that both reduces the injury risk and avoids negatively affecting performance (Davids et al., 2003; Hamill et al., 2012), but it is difficult to define the window because some characteristics of healthy runners remain unclear, e.g., the effects of running experience and fatigue on CV.

A lack of running experience may contribute to running injuries. Novice runners—those who had not been running regularly or had no running experience—were reported to experience a higher injury rate than experienced runners—those who had run a minimum weekly distance of 30km regularly for years (Buist et al., 2010; Videbæk, Bueno, Nielsen, & Rasmussen, 2015). It is unknown whether this is because years of running experience alters lower-limb coordination and CV because different lower-limb kinematic waveforms and CV were identified in runners of different training volumes (Boyer et al., 2014) and athletes of different practice skill levels (Cazzola, Pavei, & Preatoni, 2016). The effects of running experience on running mechanics have mostly been studied in the literature through comparing the motion of isolated segments or joints (Agresta et al., 2018; Schmitz et al., 2014). Thus far, only the study conducted by Floría et al. (2018) compared lower-limb coordination and CV between runners and nonrunners, and they reported limited group differences; however, in that study the running test was conducted at a relatively low physiological intensity level (an individual's comfortable speed) and only lasted for 30s.

Fatigue is another common risk factor for running-related injuries. Fatigue may alter

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running mechanics (Winter, Gordon, & Watt, 2017). Brown et al. (2016) and Dierks et al. (2010) reported that fatigue did not affect lower-limb coordination. Hafer et al. (2017) reported that in a fatigued state, CV decreased for healthy runners but increased for injured runners. Miller et al. (2008) discerned no changes in CV during an exhaustive run in both healthy and injured runners. In the aforementioned four studies, no information about the participants' running experience was provided. Although segment and joint motion have been reported to be affected by fatigue and running experience (Maas, de Bie, Vanfleteren, Hoogkamer, & Vanwanseele, 2017; Strohrmann, Harms, Kappeler-Setz, & Tröster, 2012), interactions between fatigue and running experience and lower-limb coordination and CV are unknown.

Most studies tested runners at their self-selected comfortable speed, i.e., 2.6-3.38 m/s (Dierks et al., 2010; Floría et al., 2018), or at a relatively slow fixed speed, i.e., 3.35±10% m/s (Brown et al., 2016). Anaerobic threshold speed has been considered one of the best physiological indicators of running performance (Bassett & Howley, 2000). To improve performance, runners have been encouraged to practice at or slightly above anaerobic threshold speed. Therefore, this study investigated the characteristics of lower-limb coordination and CV in the sagittal plane when both experienced and novice runners performed a prolonged run at anaerobic threshold speed. It was hypothesized that coordination pattern and variability would change with running time, and would be different between experienced and novice runners. The findings can add to the knowledge and understanding of lower-limb coordination and CV in healthy runners and provide insights into the interrelationships between running experience, fatigue, and running mechanics.

Methods

Thirty-four volunteers were recruited and divided into experienced runners, consisting of 17 recreational runners who had been running regularly for 4-20 years and had a minimum weekly running volume of 30-80 km, and novice runners, consisting of 17 volunteers who had been running regularly for fewer than 6 months. The mean (standard deviation) age, height, body mass and body mass index for experienced runners were 24.9 (6.4) years, 170.3 (6.1) cm, 63.4 (9.5) kg, and 21.8 (2.3) kg/m^2, respectively, and for novice runners were 23.8 (4.7) years, 173.1 (8.0) cm, 62.8 (10.4) kg, and 20.9 (2.3) kg/m^2, respectively. All participants reported no running-related injuries during the previous 6 months and provided informed consent. This study was approved by the university research ethics committee (Ref. No. 2015-2016-0346).

Each participant performed a 31min treadmill run at their anaerobic threshold speed, which was noninvasively determined at least 48h before the run. Kinematic data were continuously collected throughout the run. Blood lactate accumulation and perceived exertion were measured prior to and immediately after the run using a lactate meter (Nova Biomedical Corp., USA) and Borg's rating of perceived exertion (RPE) scale (6-20 points), respectively. To monitor the progression of fatigue, participants were required to report their RPE score every 5min during the run.

To determine anaerobic threshold speed, each participant performed an incremental load run on a treadmill at an initial speed of 8 km/h and increasing by increments of 1 km/h every 2min until the participant either reached 15 km/h or could not continue (Mizrahi, Verbitsky, & Isakov, 2000). Respired gas was continuously sampled and analysed in real time (Cortex Metalyzer 3B, Germany). The ratio of ventilation to oxygen consumption was calculated through averaging the breathing data from the middle 30s for each speed. anaerobic threshold was defined as the point where the ratio steeply increased (Wasserman, Whipp, Koyal, & Beaver, 1973), and the corresponding speed was the participant's anaerobic threshold speed.

Kinematic data were acquired at 200Hz using a motion capture system (Qualysis, Inc., Sweden). The system was calibrated before data collection and reported errors were within 0.5mm. Twenty-two markers were affixed separately on the bilateral anterior superior iliac spine; posterior superior iliac spine; greater trochanter; lateral and medial femoral condyle; lateral and medial malleolus; the first, second and fifth metatarsal head; and heel (middle of the shoe heel-cup), and used to define the anatomical coordinate systems, segment characteristics, and joint centres. An additional 16 markers, fixed to four rigid plastic shells (four markers each), were affixed on the lateral side of the bilateral thigh and shank to track segment motion. During data collection, the participant initially stood on the treadmill and a static calibration trial of 30s was recorded. Ten anatomical markers (the bilateral greater trochanter, lateral and medial femoral condyle, and lateral and medial malleolus markers) were then removed and the remaining 28 markers were used for tracking throughout the run. All participants wore their own running shoes and all, as determined through video analysis, were rear-foot strikers.

Kinematic data were initially processed using Visual3D (C-Motion, Inc., Rockville, MD) and further processed using Matlab (MathWorks, Inc., USA). Marker displacement data for 60s were extracted from each participant's right lower-limb from the beginning, middle, and end of the run, and were low-pass filtered at 7Hz using a second-order Butterworth filter. Joint (hip, knee, and ankle) angles and segment (pelvis, thigh, shank, and foot) orientation angles in the sagittal plane were computed. Joint angles were computed using a joint coordinate system with knee angle being defined as movements of the shank relative to the thigh (Grood & Suntay, 1983). Segment orientation angles were computed relative to the global coordinate system. Initial contact was determined by identifying the local minimum of the vertical displacement of the heel marker, and toe-off was defined as the local minimum of the knee angle after initial contact using a pattern recognition algorithm (Fellin, Rose, Royer, & Davis, 2010).

The stance phase of the middle 10 strides for each time interval was analysed and time-normalised to 100%. Running pattern was evaluated using discrete variables, which were peak angle, angle at initial contact and toe-off, range of motion, and time to peak angle. Data were averaged across the 10 strides of each interval for each participant. Standard deviation was computed across the 10 strides for each variable to quantify running variability.

Because of limitations of the continuous relative phase approach (DeLeo et al., 2004), lower-limb coordination throughout the entire stance phase was evaluated using the coupling angle by the vector coding technique approach (Brown et al., 2016; Change, van Emmerik, & Hamill, 2008; Hafer et al., 2016, 2017). An angle-angle plot was initially constructed with proximal joint/segment angle ($\theta_{proximal}$) on the horizontal axis and distal joint/segment angle on the vertical axis (θ_{distal}). The coupling angle (ø) was defined as the angle with respect to the right horizontal formed by the vector of connecting two adjacent time points for each stance phase using the following equation:

$$\emptyset_{(i,j)} = \tan^{-1} \frac{\theta_{distal_{(i,j+1)}} - \theta_{distal_{(i,j)}}}{\theta_{proximal_{(i,j+1)}} - \theta_{proximal_{(i,j)}}}$$

where ø was 0°-360° and *j* represented the percentage of the i^{th} stance phase. Couplings of interest in the current study were hip-knee flexion/extension, knee-ankle flexion/extension, pelvis-thigh sagittal rotation, thigh-shank sagittal rotation, and shank-foot sagittal rotation, which have been used in previous studies for investigating running coordination and is also thought to be related to RRIs (Floría et al., 2018; Hafer et al., 2016, 2017; Heiderscheit et al., 2002). The coordination pattern, which indicated the relative rotation direction of the two joints or segments of the coupling of interest, was divided into the following categories: in-phase motion (22.5°<ø<67.5° or 202.5°<ø<247.5°, both joints or segments rotated simultaneously in the same direction), anti-phase motion (112.5°<ø<157.5° or 292.5°<ø<337.5°, the two joints or segments simultaneously rotated in opposite directions), proximal motion phase (0°<ø<22.5° or 157.5°<ø<202.5° or 337.5°<ø<360°, the proximal joint or segment rotated while the other was fixed), and distal motion phase (67.5°<ø<112.5° or 247.5°<ø<292.5°, the distal joint or segment rotated while the other was fixed) (Chang et al., 2008).

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To conduct further analysis, as in other studies (Floría et al., 2018; Hein et al. 2012), the stance phase was divided into four sub-phases: loading stance, defined as the initial 20% of the stance phase; midstance, from 21% to 50% of the stance phase; terminal stance, from 51% to 80% of the stance phase; and pre-swing, the final 20% of the stance phase. Frequency of each coordination pattern across the stance phase and the four sub-phases was computed and described in percentage of stance phase (Chang et al., 2008; Hafer et al., 2016; Hein et al., 2012), and then averaged across the 10 strides at each interval for each participant to quantify various functional demands during the run. Standard deviation of the coupling angle at each percentage of the stance phase was computed across the 10 strides to quantify CV (Floría, 2018; Hafer et al., 2016, 2017). The standard deviation was averaged across the stance phase and each sub-phases at each interval for each participant to describe the CV.

Data were analysed using statistical software (SPSS version 21.0, IBM Inc., Chicago, IL, USA). Group differences for age, height, body mass, and AT speed were analysed using independent samples *t*-tests. Running speed affected the results, and a significant difference between groups with respect to anaerobic threshold speed was evident ($p<0.001$); therefore, two-way (groups: experienced and novice runners; time: beginning, middle, and end) repeated-measures analysis of covariance was performed to examine differences in running patterns and variability, coordination patterns and variability after eliminating the variance attributable to running speed. *Post-hoc* comparisons were conducted on the basis of the least significant difference criterion. The statistical significance level was set at $p=0.05$. The magnitude of difference was estimated and expressed as the Cohen's *d* effect size.

Results

No group differences were observed in age ($p=0.20$, $d=0.24$), height ($p=0.66$; $d=0.57$), and body mass ($p=0.18$; $d=0.11$). The anaerobic threshold speed of experienced runners was 12.6

(1.3) km/h, which was faster than the 11.1 (0.8) km/h speed of novice runners (p<0.001, d=1.50). Before the run, blood lactate accumulation levels of experienced and novice runners were 1.3 (0.8) mmol/L and 1.3 (0.5) mmol/L, respectively, and self-reported RPE scores were 7.6 (2.1) and 7.2 (1.2), respectively. After the run, the blood lactate accumulation levels reached 8.0 (2.0) mmol/L for experienced runners and 7.4 (1.5) mmol/L for novice runners, and RPE scores were 17.5 (0.9) ('very hard') and 18.3 (0.9) ('extremely hard'), respectively.

No group-by-time interactions were discerned for kinematics except the time to peak hip angle (p=0.020, d=0.42) (Figure 1a), which was similar between experienced and novice runners at the beginning of the run, but decreased significantly for experienced runners and remained relatively constant for novice runners during the run. No group or time effect on kinematics was observed.

No group-by-time interaction was revealed, but a significant group effect for joint or segment kinematic variability was evident (Figure 2). Compared with novice runners, experienced runners exhibited smaller variabilities in peak hip angle (p=0.038, d=0.43), peak knee angle (p=0.005, d=0.63), peak thigh angle (p=0.003, d=0.55), and thigh angle at initial contact (p=0.017, d=0.47). A time effect was only evident for variability of the knee angle at toe-off (p=0.043, d=0.40), but a *post-hoc* comparison did not indicate significant differences.

A significant group-by-time interaction was evident for coordination pattern (anti-phase motion for hip-knee coupling during midstance, p=0.022, d=0.42; in-phase motion for pelvis-thigh coupling during the stance phase and midstance, p=0.028, d=0.41 and p=0.018, d=0.42, respectively). For hip-knee coupling (Figure 1b), the percentage of anti-phase motion during midstance for experienced runners was less than novice runners at the beginning, and increased with time for experienced runners and maintained unchanged throughout the run for novice runners. For pelvis-thigh coupling (Figure 1c, d), the percentage of in-phase motion during the stance phase and midstance for experienced runners was higher than novice runners; during the run it decreased in the middle and increased at the end for experienced runners but initially increased then decreased for novice runners. Time effects were evident (Figure 3). For pelvis-thigh coupling, the pelvis motion phase during the stance phase significantly increased with time (p=0.020, d=0.42). The thigh motion phase for thigh-shank coupling during midstance and the shank motion phase for shank-foot coupling during the stance phase increased with time (p=0.041 and 0.048; d=0.41 and 0.40, respectively), but *post-hoc* comparisons revealed no significant differences for shank-foot coupling. Significant group effects were evident (Figure 4). Compared with novice runners, experienced runners displayed a higher percentage of knee motion phase for hip-knee coupling during midstance (p=0.024, d=0.45), in-phase motion for knee-ankle coupling during midstance (p=0.040, d=0.43), pelvis motion phase for pelvis-thigh coupling during the stance phase (p=0.005, d=0.63), loading stance (p=0.007, d=0.51), and midstance (p=0.039, d=0.43), and shank motion phase for thigh-shank coupling during the stance phase (p=0.026, d=0.45), but a lower percentage of ankle motion phase for knee-ankle coupling during midstance (p=0.048, d=0.12), and thigh motion phase for pelvis-thigh coupling during the stance phase (p=0.042, d=0.13) and midstance (p=0.012, d=0.49).

No group-by-time interaction or time effect was evident for CV. Group effects were evident for CV, but significant differences were revealed for a few parameters (Figure 5). Experienced runners exhibited more CV for hip-knee coupling during terminal stance and shank-foot coupling during the stance phase compared with novice runners.

Discussion

This study investigated running mechanics through examining lower-limb coordination and CV of experienced and novice runners who performed a prolonged treadmill run at anaerobic threshold speed. Both segment-to-segment and joint-to-joint coupling motions were analysed to obtain a full view of lower-limb coordination from different levels during the run. The results demonstrate the presence of a group-by-time interaction on lower-limb coordination patterns, and significant group differences in joint and segment kinematic variability and CV.

The ankle and knee play dominant roles in shock attenuation during landing, but hip flexion also helps to absorb impact (Dugan & Bhat, 2005; Schache, Bennell, Blanch, & Wrigley, 1999). In this study, the time to peak hip angle exhibited no group difference at the beginning, but it reduced over time for experienced runners and remained unchanged for novice runners. This may indicate that experienced runners adapt more favourably to fatigue than novice runners, perhaps because experienced runners could adjust their hip motion to improve shock absorption. However, a significant interaction was only observed for the time to peak hip angle with moderate effect size.

With respect to lower-limb coordination, at the beginning, experienced runners exhibited a higher percentage of in-phase motion for pelvis-thigh coupling during the stance phase and midstance but a lower percentage of anti-phase motion for hip-knee coupling during midstance than novice runners. Because impact absorption relies on proper lower-limb coordination (Stergiou, Bates, & James, 1999; Stergiou, Jensen, Bates, Scholten, & Tzetzis, 2001), more in-phase motion could improve efficiency during shock attenuation but more anti-phase motion could worsen it. No group differences in anti-phase motion for hip-knee coupling during midstance at the end of the run, but experienced runners nevertheless displayed more in-phase motion for pelvis-thigh coupling during the stance phase and midstance than novice runners in a fatigued state. To date, no study has been reported any interactions between running experience, fatigue, and coordination pattern, but interactions have reported for the motion of segments and joints (Maas et al., 2017; Strohrmann et al., 2012) and temporal parameters (Mo & Chow, 2018). For instance, compared with experienced runners, novice runners have displayed more changes in hip abduction and more trunk forward leaning in a fatigued state (Maas et al., 2017; Strohrmann et al., 2012). All these studies have demonstrated the benefits

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of years of running experience that may enable experienced runners to achieve better adaptation of the locomotor system to progressive fatigue.

The present study revealed no group differences in joint and segment kinematics, which was consistent with the findings reported by Agresta et al. (2018); they acquired trunk and lower-limb kinematic data from 100 runners with various degrees of running experience and discerned no significant correlation between running experience and kinematics. However, the current study ascertained significant group differences in lower-limb coordination; experienced runners displayed more in-phase motion but less ankle motion phase for knee-ankle coupling during midstance and more pelvis motion phase but less thigh motion phase for pelvis-thigh coupling compared with novice runners, which was partially consistent with the study of Floría et al. (2018); they discovered that runners exhibited more in-phase motion for hip-knee coupling and less in-phase motion for knee-ankle coupling compared with nonrunners. However, in that study (Floría et al., 2018), coordination was quantified using continuous relative phase, which was computed using both angular displacement and velocity, and they did not eliminate the effects of running speed, as runners ran at faster speeds (3.4±0.4 m/s) than nonrunners (2.8±0.2 m/s). The contradictory results evident in the current study and the study by Floría et al. (2018) may be because coordination is a goal-directed behaviour (Davids et al., 2003). Overall, experienced and novice runners exhibited unique coordination patterns during landing, and more in-phase motion for experienced runners may demonstrate the benefits of long-term running practice.

Additionally, experienced runners revealed less joint and segment kinematic variability than novice runners. This may be attributable to years of practice that has optimised running patterns and reduced variances. A consistent finding has been reported, indicating that experienced runners exhibit less stride time variability than novice runners (Mo & Chow, 2018; Nakayama, Kudo, & Ohtsuki, 2010). However, these studies were based on task outcome variability. Variability during task execution (i.e., CV) is interpreted differently, and is linked to adaptability and flexibility of the locomotor system (Hamill et al., 2012): more CV indicates more flexibility during task execution. The current study determined that experienced runners exhibited more CV of hip-knee coupling during terminal stance and shank-foot coupling during the stance phase than novice runners, which may indicate greater flexibility for experienced runners during landing; this flexibility may reduce the risk of running injuries (Hamill et al., 2012). Floría et al. (2018) found that nonrunners displayed a moderate increase in CV compared with runners, which was inconsistent to the current finding; however, they did not eliminate the effects attributable to speed differences.

Regardless of running experience, fatigue greatly affected lower-limb coordination, which was evident in increased pelvis motion phase for pelvis-thigh coupling in the stance phase and thigh motion phase for thigh-shank coupling in midstance in a fatigued state. Studies have reported that lower-limb coordination remains unchanged in a fatigued state (Dierks et al., 2010; Brown et al., 2016), but they observed fatigue-induced changes in hip joint motion. In these studies, coordination of joint couplings was quantified using different approaches, joint timing (Dierks et al., 2010) and continuous relative phase (Brown et al., 2016), which make it not comparable to the current study. Nevertheless, similar to the two aforementioned studies, fatigue-induced changes around the hip joint were observed in the current study (pelvis-thigh coupling), which may indicate that runners adapt to the progression of fatigue by adjusting the motion of the proximal segment or joint close to the core (pelvis, hip, and thigh). More supporting evidence has been reported in the literature; fatigue-induced changes have been identified in trunk and hip motion (Koblbauer, van Schooten, Verhagen, & van Dieën, 2014; Maas et al., 2017).

The current study had several limitations. First, only motion in the sagittal plane was analysed. Future studies that involve motion in the transverse and frontal planes should be

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undertaken. In addition, the running test was conducted only at anaerobic threshold speed. Because of the association between running speed and kinematics, it is unclear whether similar findings will be obtained when running at other speeds (e.g. preferred speed). Finally, a longitudinal study may meaningfully help to understand the influences of running experience on lower-limb coordination and CV.

Conclusion

Both running experience and fatigue affected lower-limb coordination. Experienced and novice runners exhibited different lower-limb coordination patterns during the prolonged treadmill run at anaerobic threshold speed: more in-phase motion for pelvis-thigh and knee-ankle couplings during midstance for experienced runners and more thigh motion phase for pelvis-thigh and anti-phase motion for hip-knee coupling during midstance for novice runners. With the progression of fatigue, experienced runners adapted by adjusting the motion of the proximal segments and joints (i.e., pelvis, hip, and thigh) with greater CV, and novice runners adapted by altering the motion of the distal segments and joints (i.e., shank, ankle, and foot), exhibiting greater variability of hip, knee, and thigh motion. The current findings demonstrated that experienced and novice runners could maintain anaerobic threshold speed for 31 min using different strategies.

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Figure captions

Figure 1. Time to peak hip angle (a) and coordination patterns for hip-knee coupling (b) and pelvis-thigh coupling (c, d) for experienced runners (blue) and novice runners (red). Lines represent median values.

Figure 2. Variability of joint and segment kinematics for experienced runners (black) and novice runners (blue) at beginning (dot), middle (square), and end (triangle). Lines represent median values.

Figure 3. Coordination pattern for pelvis-thigh coupling during stance phase (a) and midstance (b).

*, time effect, $p < 0.05$.

Figure 4. Coordination pattern for pelvis-thigh coupling, hip-knee coupling and knee-ankle coupling for experienced and novice runners.

#, group effect, $p < 0.05$.

Figure 5. Coordination variability for hip-knee coupling (a) and shank-foot coupling (b) for experienced runners (black) and novice runners (blue) at beginning (dot), middle (square), and end (triangle). Lines represent median values.

Figure 1

Figure 1

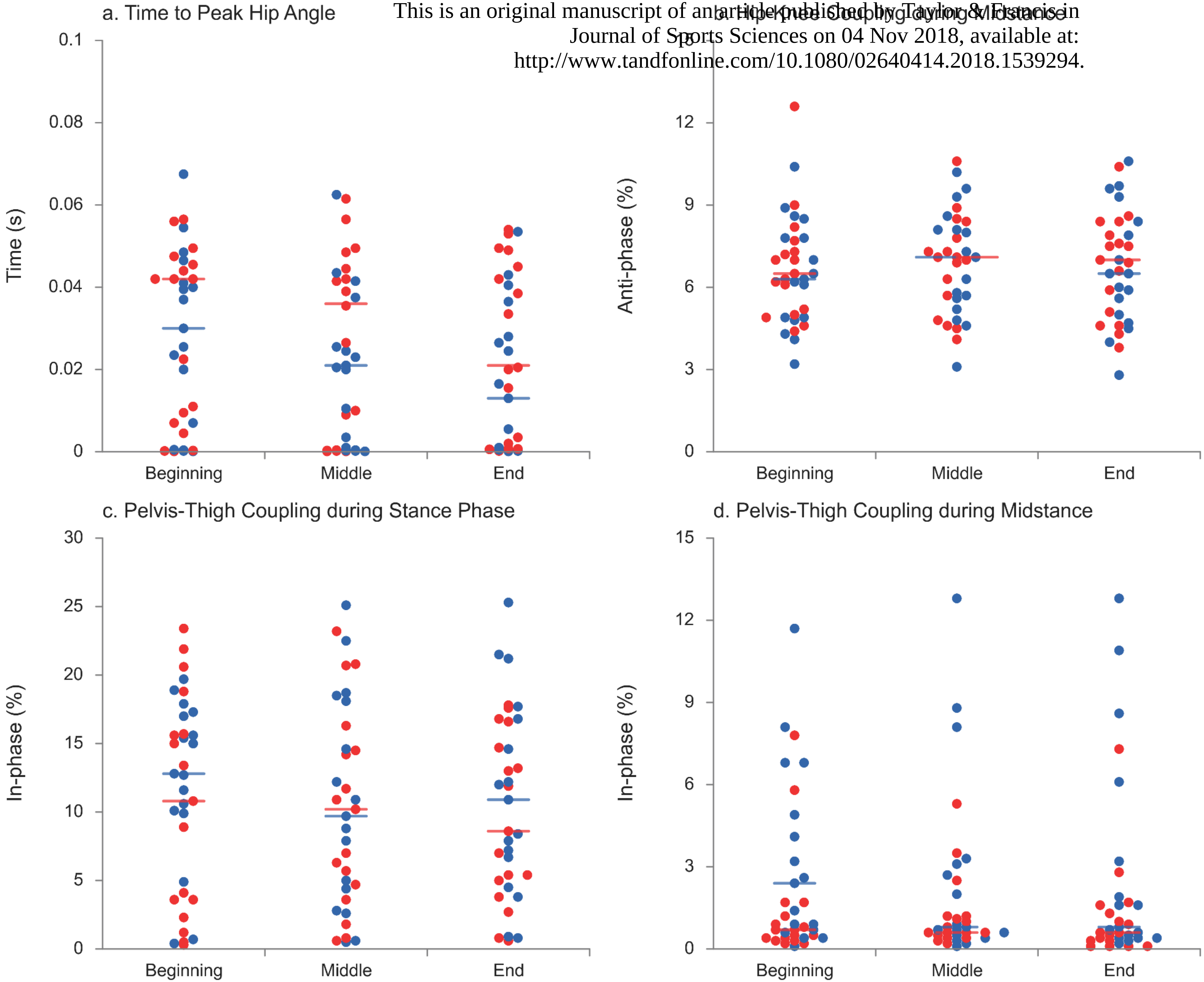

Figure 2

Figure 2

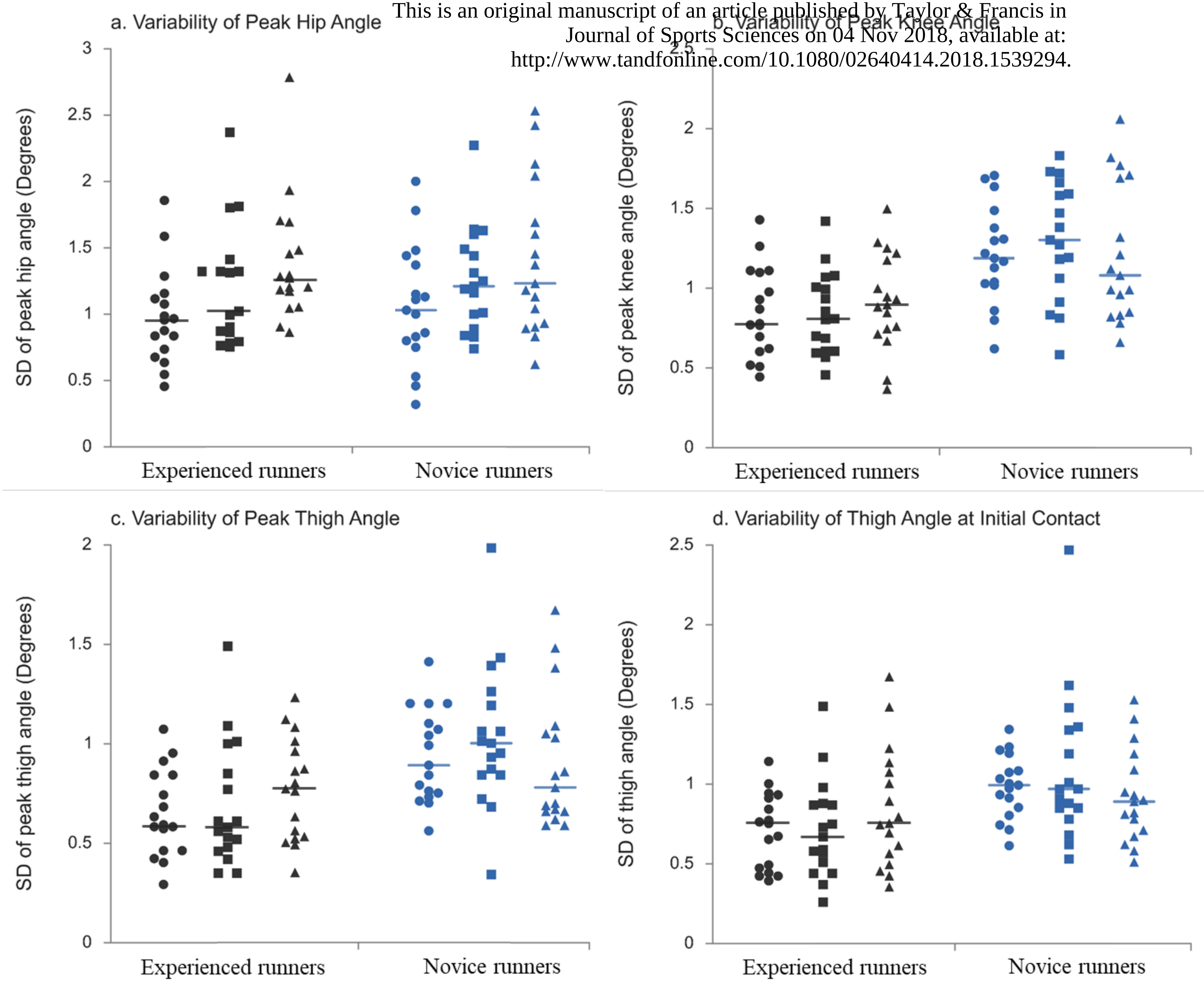

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Figure 3

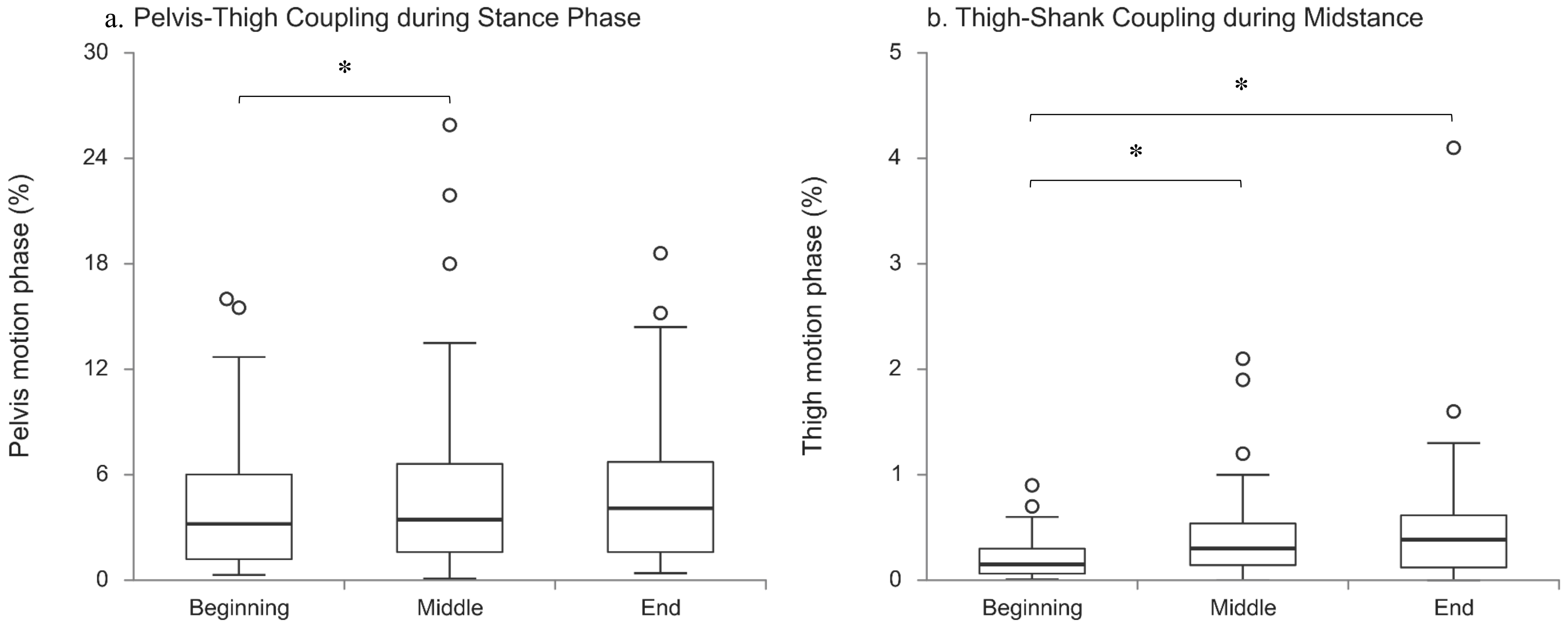

Figure 4

Figure 4

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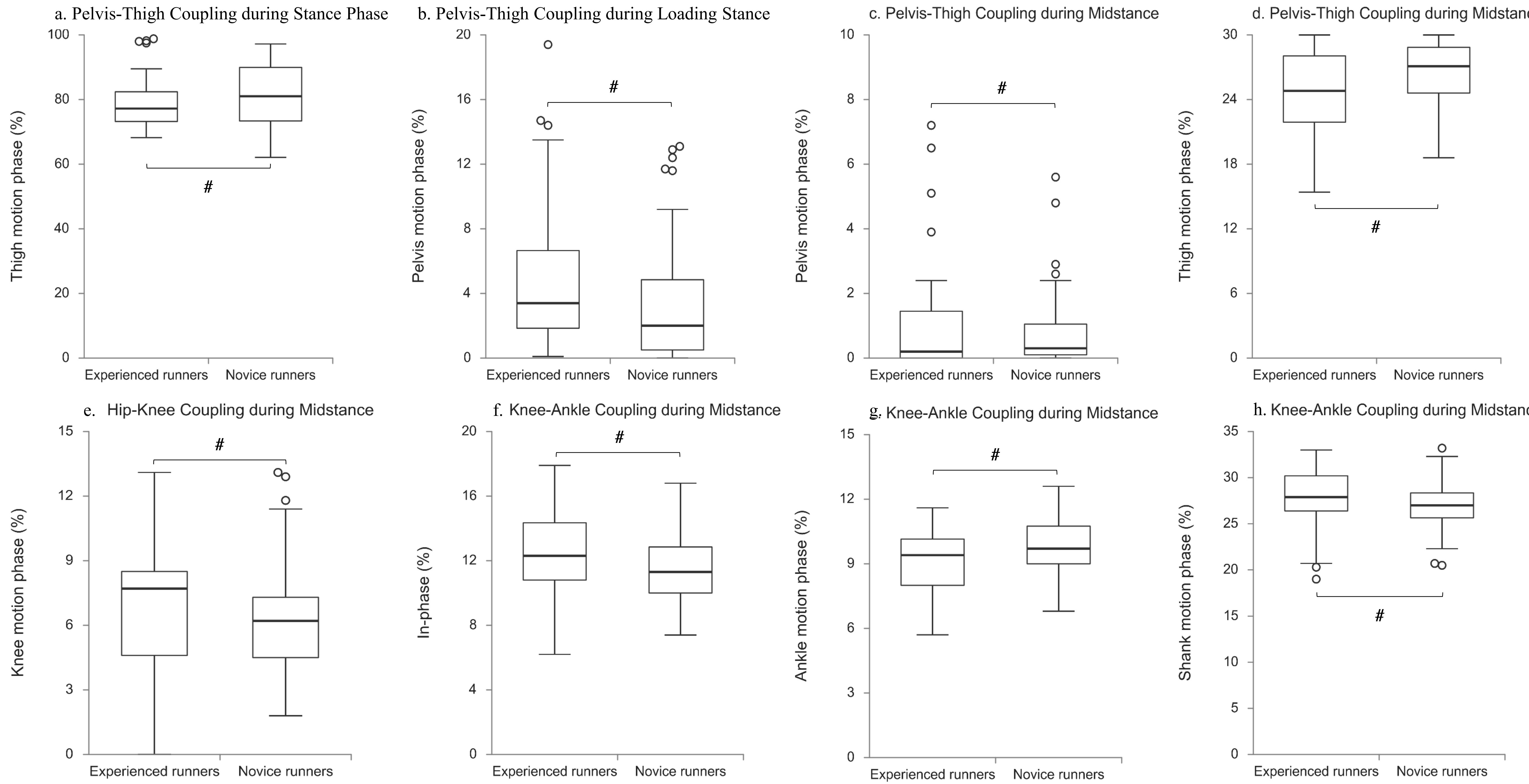

Figure 5
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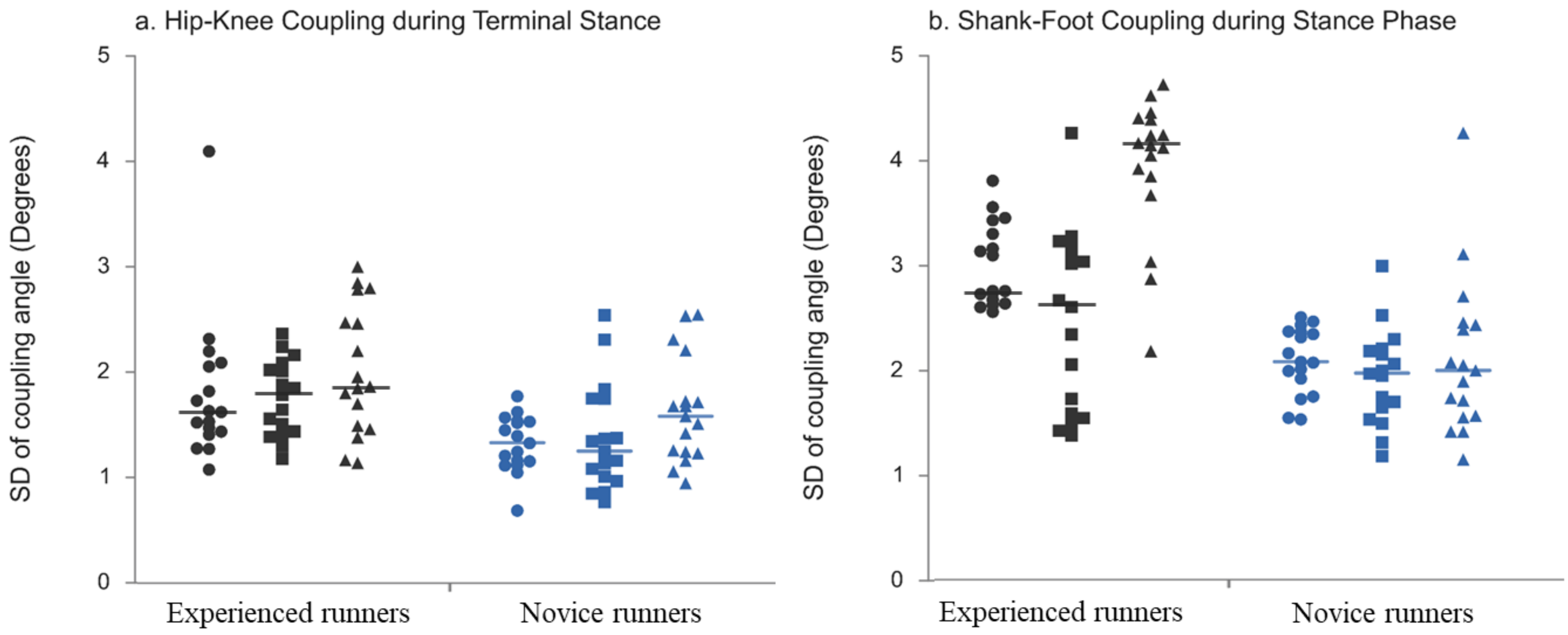

Biographical notes on all contributors

Shiwei Mo is a Ph.D. student of The Education University of Hong Kong. He is interested in gait analysis, motor control, and sports biomechanics. His previous studies have been published in journals such as Gait & Posture and Ergonomics.

Daniel H.K. Chow is a Chair Professor of Health and Sports Science at the Education University of Hong Kong. He received a PhD in bioengineering from the University of Strathclyde, Glasgow, Scotland in 1992.