Title

The effect of running speed on joint coupling coordination and its variability in recreational runners

Author names and affiliations

Pablo Floría[a], Alberto Sánchez-Sixto[b], Andrew J. Harrison[c], Reed Ferber[d, e]

[a] Universidad Pablo de Olavide, Physical Performance & Sports Research, Seville, Spain. pfloriam@upo.es

[b] Department of Sport, CEU San Pablo University, Spain. asanchezsixto@ceuandalucia.es

[c] Biomechanics Research Unit. University of Limerick. Limerick, Ireland. drew.harrison@ul.ie

[d] Running Injury Clinic, Calgary, Canada

[e] University of Calgary, Calgary, Canada. rferber@ucalgary.ca

Abstract

The purpose of this study was to examine the effect of speed on coordination and its variability in running gait using vector coding analysis. Lower extremity kinematic data were collected for thirteen recreational runners while running at three different speeds in random order: preferred speed, 15% faster and 15% lower than preferred speed. A dynamical systems approach, using vector coding and circular statistics, were used to quantify coordination and its variability for selected hip-knee and knee-ankle joint couplings. The influence of running speed was calculated from the continuous data sets of the running cycle, allowing for the identification of time percentages where differences existed. Results indicate that increases in running speed produced moderate alterations in the frequency of movement patterns which were not enough to alter classification of coordination. No effects of speed on coordination variability were observed. This study has demonstrated that coordination and coordination variability is generally stable in the range of ±15% around of preferred speed in recreational runners.

Keywords

Vector coding, circular statistics, dynamical systems, lower extremity

Highlights

- Coordination during running at different speeds was quantified using modified vector coding technique

- The classification of coordination pattern did not change across running speeds

- Differences in the percentage of time of each coordination pattern were found mainly in early stance

- Coordination variability was not sensitive to changes in running speed

1. Introduction

Running is an important cyclical activity, which is critical to the performance of many sports. It is estimated that the cadence during a marathon is approximately 1.42 strides per second (Chan-Roper, Hunter, Myrer, Eggett, & Seeley, 2012) and although the stride is frequently repeated, some degree of coordination variability is expected in the movements involved (Miller, Chang, Baird, Van Emmerik, & Hamill, 2010). In recent years, coordination variability has emerged in the literature due to its links with various factors such as: injury status, (DeLeo, Dierks, Ferber, & Davis, 2004; Hamill, Van Emmerik, Heiderscheit, & Li, 1999; Miller, Meardon, Derrick, & Gillette, 2008), skill level (Nakayama, Kudo, & Ohtsuki, 2010), running form (Hafer, Silvernail, Hillstrom, & Boyer, 2016), sex (Boyer, Silvernail, & Hamill, 2017) and/or aging (Boyer et al., 2017; Silvernail, Boyer, Rohr, Brüggemann, & Hamill, 2015).

Despite the growing interest in coordination variability in running, there remains a lack of clarity on how to interpret the variability data. For example, the magnitude of coordination variability has been suggested as an indicator of the adaptability of the runner to generated motor patterns capable of responding to disturbances or changes in environmental conditions (Bernstein, 1967). Although extreme values of coordination variability, in either direction have been shown to be related to an elevated injury risk or decreased level of performance (Hamill, Palmer, & Van Emmerik, 2012; Seifert, Button, & Davids, 2013), however, many of these aforementioned experiments involve running under one condition and may not necessarily reflect real-world situations indicative of training.

Although running is a cyclic skill, it is not always executed under the same conditions. Therefore, it is quite normal for a runner to modify various aspects of practice within or between sessions, including: the running surface (ground, treadmill, etc.), the running technique (e.g. changes in the running form as well as the cadence) or the aim of the practice (e.g. to achieve

intensity or volume). Relatively little is known about how coordination variability responds to changes in practice conditions. Recent studies have suggested that the imposition of a constant speed via treadmill running, could diminish the coordination variability due to a reduced need to adapt to environmental variation (Cazzola, Pavei, & Preatoni, 2016; Lindsay, Noakes, & McGregor, 2014; Wheat, Baltzopoulos, Milner, Bartlett, & Tsaopoulos, 2005). In addition, Hafer et al., (2016) found that coordination variability decreased as running cadence increased and therefore suggested that changes in coordination variability could be a consequence of the individual responding to new constraints in the task. This suggests that changes in the magnitude of coordination variability could provide a useful metric to monitor the level of mastery in a new, but related task.

Of the many factors that are often modified during training sessions, speed is a measure of the physical demand of the task. Increases in speed often result in an increase in stride length and/or frequency, which is usually accompanied by an increase in joint range and joint torque (Orendurff et al., 2018). The determinative impact of speed on running biomechanics may also be reflected in coordination and its variability. Seay, Van Emmerik and Hamill (2011) suggested that running speed influenced coordination level, but Mehdizadeh, Arshi and Davids (2015) advised that the magnitude of this effect depended on the joint-coupling of interest. Contradictory results have been found regarding the effect (Bailey, Silvernail, Dufek, Navalta, & Mercer, 2018) or non-effect (Mehdizadeh et al., 2015; Seay et al., 2011) of speed on coordination variability. These conflicting results could be due to the differences in the joint-couplings and speed ranges examined. The studies cited above, analysed the effect of velocity on coordination using the continuous relative phase technique. Running coordination has also been analysed using the vector coding technique (Brown, Zifchock, Hillstrom, Song, & Tucker, 2016; Hafer & Boyer, 2017; Rodrigues, Chang, TenBroek, Van Emmerik, & Hamill, 2015),which provides information about movement patterns in a simpler way to interpret

compared to continuous relative phase (Van Emmerik, Miller, & Hamill, 2013). This technique classifies coordination into four patterns: 1. In-phase, where joints couples rotate in the same direction; 2. antiphase, where joint couples rotate in opposite directions; 3. distal phase, where the distal joint rotates exclusively; and 4. proximal phase, where the proximal rotates exclusively. This technique should be useful in gaining insight into the organization of movement underlying running speed.

Quantifying the adjustments in coordination and coordination variability provide insights on the level of challenge required to induce changes in the running speed. Modifications in coordination could indicate the need to alter the movement pattern to accomplish the demands of the new task. While changes in the coordination variability could indicate the degree of adaptability that the runner requires to respond to new constraints in the task. Consequently, the objective of this study was to examine the effect of speed on the joint-coupling coordination and coordination variability in running gait. A vector coding technique was used to assess coordination and its variability in recreational runners while running at three different speeds. It was hypothesized that there would be differences in coordination and coordination variability between running speeds. Specifically, we expect to find a greater percentage of movement time in distal coordination with increased running speed. Previous studies (Orendurff et al., 2018) have highlighted the important role of the ankle in the increase of speed in recreational runners. Furthermore, it was expected that the coordination variability should decrease with the increase in running speed in response to the increased in task demand.

2. Methods

Thirteen healthy recreational runners (males, age: 22.66 ± 1.37 years, height: 1.75 ± 0.05 m and body mass: 79.79 ± 12.30 kg) volunteered to participate in this study. All participants ran a minimum of 12 km per week and had been free from any lower extremity musculoskeletal injury in the previous 12 months. The study had ethical approval from the University Research Ethics Committee and all participants signed informed consent forms before participating in the study.

A familiarization session was completed before the experiment to ensure that none of the participants had difficulty in treadmill running. This familiarization session also served to determine the preferred speed for each participant (self-selected speed).

A 5-camera VICON motion capture system (Bonita-3, Vicon Motion Systems, Oxford, UK), and 9 mm retro-reflective markers, were used to collect 3-dimensional (3D) kinematic data at 200 Hz during treadmill running (Magna Pro, BH, Spain). Marker locations were consistent with Pohl, Lloyd and Ferber (2010), with 14 anatomical markers attached bilaterally to: the greater trochanters, medial and lateral knee joint lines and medial and lateral malleoli. Technical marker clusters, glued to a rigid plastic shell, were placed on the pelvis (three markers), and bilateral thigh and shank (four markers each) with self-adhering straps. Three markers were taped to the heel counter of each of the standard running shoes (Nike, Air Pegasus). These twenty-five markers represented seven rigid segments.

Following placement of all the anatomical and segment markers, the participant stood for a static trial where position was controlled using a graphic template placed on the treadmill with feet positioned 0.3 m apart and pointing straight ahead. Once the feet were placed in the standardized position, the participant crossed their arms over their chest and stood still while one-second of marker location data were recorded to identify joint centre locations and to calculate the segment coordinate systems.

Participants were allowed a 5 minute warm-up on the treadmill at their preferred running pace. Next, each participant ran for 5 min at three different speeds in random order: preferred speed, 15% faster that preferred speed (+15%), and 15% slower that preferred speed (-15%). Marker trajectory data were recorded for 30 seconds during last minute of each speed trial. Marker trajectories were filtered with a 10 Hz low-pass, 2nd order recursive Butterworth filter and 3D rigid body kinematics were calculated using 3D GAIT software (Running Injury Clinic Inc., Calgary, Alberta, Canada). Kinematic data were calculated based on a single value decomposition approach outlined by Söderkvist and Wedin (1993) and the joint coordinate system suggested by Cole, Nigg, Ronsky and Yeadon (1993).

The dataset of each parameter was normalized to 101 points using a piecewise linear length normalization procedure (Helwig, Hong, Hsiao-Wecksler, & Polk, 2011). This technique expands or compresses the time axis to ensure temporal alignment at points of interest (Sadeghi et al., 2000). Two points of interest (foot strike and toe off) were identified which defined two subphases of the stride cycle. The stance phase was defined from foot strike to the toe off and the swing phase was from toe off to foot strike. To detect the timing of foot strike and toe off events, a principal component analysis combined with a machine learning approach was used (Osis, Hettinga, & Ferber, 2016; Osis, Hettinga, Leitch, & Ferber, 2014). This allowed all angle-time curves to be expressed over normalized periods (percentage time), such that individual data could be aligned to identifiable events. Additionally, the stance phase was divided into three phases: early, mid, and late stance (thirds of stance phase) similar to previous studies (Boyer et al., 2017; Hafer & Boyer, 2017).

Joint coordination was calculated for hip flexion/extension and knee flexion/extension ($HIP_{flex/ex}$-$KNEE_{flex/ex}$), hip abduction/adduction and knee flexion/extension ($HIP_{abd/ad}$-$KNEE_{flex/ex}$), knee flexion/extension and ankle flexion/extension ($KNEE_{flex/ex}$-$ANKLE_{flex/ex}$), knee flexion/extension and subtalar inversion/eversion ($KNEE_{flex/ex}$-$ANKLE_{in/ev}$). These joint

couplings were selected based on their importance for enhancing running performance (Schache, Dorn, Williams, Brown, & Pandy, 2014) and previous research on kinematic couplings in runners (Cunningham, Mullineaux, Noehren, Shapiro, & Uhl, 2014; Dierks & Davis, 2007; Hafer & Boyer, 2017; Hein et al., 2012; Kurz, Stergiou, Buzzi, & Georgoulis, 2005; McClay & Manal, 1997; Wheat et al., 2005). Joint angles of interest were normalized to 100 points per running cycle and ten strides of data were extracted and analysed.

Joint coordination and coordination variability was calculated using MATLAB vector coding script implementing functions from the CircStat circular statistics toolbox (Berens, 2009). In brief, angle-angle plots of the coupling of interest were created and coupling angles (γ) were calculated as the angle subtended from a vector adjoining two successive time points relative to the right horizontal (Van Emmerik et al., 2013):

$$\gamma_{j,i} = tan^{-1}\left(\frac{y_{(j,i+1)} - y_{j,i}}{x_{(j,i+1)} - x_{j,i}}\right) (1)$$

Where $0 \leq \gamma \leq 360º$ and i is a percent running cycle of the jth trial. Due to directional nature of coupling angle, the average coupling angle ($\overline{\gamma}_i$) was calculated from the mean horizontal ($\overline{x}_i$) and vertical ($\overline{y}_i$) components across the multiple running cycles for each percentage of stance (Van Emmerik et al., 2013):

$$\overline{x}_i = \frac{1}{n}\sum_{j=1}^{n}(\cos\gamma_{j,i}) (2)$$

$$\overline{y}_i = \frac{1}{n}\sum_{j=1}^{n}(\sin\gamma_{j,i}) (3)$$

$$\overline{\gamma}_i = \begin{cases} tan^{-1}(\overline{y}_i/\overline{x}_i) \ if \ \overline{x}_i > 0 \\ 180 + tan^{-1}(\overline{y}_i/\overline{x}_i) \ if \ \overline{x}_i < 0 \end{cases} (4)$$

The coupling angle represents an instantaneous spatial relationship from which four unique coordination patterns can be identified: Antiphase, in-phase, proximal joint phase, and distal joint phase (Chang, Van Emmerik, & Hamill, 2008). The four coordination patterns emerge from the classification scheme that divides the polar distribution into bins of 45 each. In-phase couples (centred on the 45º and 225º positive diagonal) rotate in the same direction. Antiphase

couples (centred on the 135º and 315º negative diagonal) rotate in opposite directions. Phase couples dominated by a single joint occur when the coupling angles are parallel the horizontal (0º or 180º: proximal phase in which the proximal joint rotates exclusively) or parallel to vertical (90º or 270º: distal phase in which the distal joint rotates exclusively). To provide qualitative information on the movement coordination throughout the entire movement, a binning frequency analysis was executed (Silvernail, Van Emmerik, Boyer, Busa, & Hamill, 2018). For each portion of gait cycle, the frequency of each coordination pattern was determined. A 1-way repeated-measures ANOVA was used to compare coordination pattern frequency between running speed conditions. Bonferroni-adjusted pairwise comparisons were performed between the self-selected speed and faster or slower speeds. The statistical significance level was set at $P < .05$. Statistical analysis was completed by the estimation of the effect size using Cohen's dz (1977) to evaluate the magnitude of differences. The criteria to interpret the effect size were: trivial = 0.00–0.19; small = 0.20–0.59; moderate = 0.60–1.19; large = 1.20–1.9; very large = 2.0–4.0; and nearly perfect > 4.0 (Hopkins, 2006).

Coordination variability was calculated as the circular standard deviation of the coupling angle at each individual point of the running cycle across ten strides. Measures of coordination variability were analysed using statistical parametric mapping (SPM, Pataky, Vanrenterghem, & Robinson, 2015). Specifically, a SPM one-way repeated-measures ANOVA was used to detect significant differences between coordination variability waveforms at the three different speeds. All SPM analyses were implemented using the open-source spm1d code (v.M0.1, www.spm1d.org) in MATLAB.

3. **Results**

Participants ran at 2.74 ± 0.30 m·s^{-1} (-15%); 3.19 ± 0.33 m·s^{-1} (self-selected); and 3.66 ± 0.40 m·s^{-1} (+15%); these speeds approximately correspond to 6:05-, 5:14-, and 4:34-min/km running paces.

The frequency of each coordination pattern during the gait cycle for the three speed conditions are shown in tables 1 and 2. Neither the increase nor the decrease in speed running with respect to the self-selected speed resulted in clear differences in the classification of coordination throughout the gait cycle. For the sagittal hip vs. sagittal knee joint couple, a knee coordination pattern was observed during early and swing phases, while an in-phase coordination pattern was displayed in mid and late stance phases (Table 1). For the frontal hip vs. sagittal knee joint couple, a clear knee pattern was observed during midstance and swing phases, while in early and late phases, no clear pattern was observed and knee and antiphase coordination reached similar values in those phases (Table 1). For the sagittal knee vs. sagittal ankle couple, only in the swing phase displayed a clear knee coordination pattern (Table 2). For the sagittal knee vs. frontal ankle couple, a knee coordination pattern was observed throughout the gait cycle (Table 2).

Although a ±15% change in the running speed was not sufficient to modify the classification of coordination, moderate differences in frequency of each coordination pattern were found when the speed increased (tables 1 and 2). In the early phase, a lower knee coordination pattern frequency was observed in frontal hip vs. sagittal knee and frontal ankle vs. sagittal knee couples. During this phase, the frequency in which the sagittal knee vs. sagittal ankle displayed an ankle coordination pattern increased. During midstance phase, a greater in-phase coordination pattern frequency was found in the sagittal knee vs. sagittal ankle couple. Finally, the frequency of the knee coordination pattern in the sagittal knee vs. sagittal ankle couple increased during swing phase.

Figure 2 illustrates the coordination variability for the three speeds during the running cycle. The results also showed that the coordination variability scores were different throughout the entire stride. In the time series data, four peaks of coordination variability were observed which occurred during the transition between early and mid phases ($HIP_{flex/ex}$-$KNEE_{flex/ex} > 11°$, $HIP_{abd/ad}$-$KNEE_{flex/ex} > 24°$, $KNEE_{flex/ex}$-$ANKLE_{flex/ex} > 12°$, $KNEE_{flex/ex}$-$ANKLE_{in/ev} > 25°$), as well as between late and swing phases ($HIP_{flex/ex}$-$KNEE_{flex/ex} > 14°$, $HIP_{abd/ad}$-$KNEE_{flex/ex} > 24°$, $KNEE_{flex/ex}$-$ANKLE_{flex/ex} > 13°$, $KNEE_{flex/ex}$-$ANKLE_{in/ev} > 23°$). Two peaks were found during swing phase, one in the middle ($HIP_{flex/ex}$-$KNEE_{flex/ex} > 20°$, $HIP_{abd/ad}$-$KNEE_{flex/ex} > 16°$, $KNEE_{flex/ex}$-$ANKLE_{flex/ex} > 19°$, $KNEE_{flex/ex}$-$ANKLE_{in/ev} > 30°$), and at the end of phase ($HIP_{flex/ex}$-$KNEE_{flex/ex} > 14°$, $HIP_{abd/ad}$-$KNEE_{flex/ex} > 16°$, $KNEE_{flex/ex}$-$ANKLE_{flex/ex} > 23°$, $KNEE_{flex/ex}$-$ANKLE_{in/ev} > 27°$).

A change of ±15% in running speed with respect to the self-selected speed had no effect on the coordination variability. SPM analysis showed no statistical significant differences in coordination variability during the running cycle in any the four joints couplings analysed ($F < 5.54$, $P > .05$).

4. **Discussion**

The purpose of this study was to investigate the effect of changes in running speed on the joint-coupling coordination and coordination variability using a vector coding technique. The results showed that the classification of the coordination pattern throughout the running gait cycle was not sensitive to a relatively small change in the speed (±15%) for recreational runners; although moderate differences were found in the duration over which each pattern was displayed. These results provided some evidence to reject the hypothesis of this study, because the differences found in the coordination pattern were limited and moderate. This could be due to both the magnitude of the speed variation and joint couples analysed. Seay et al. (2011) observed that a 65% of speed variation caused changes in the pelvis-trunk coordination. Whereas Bailey et al. (2018) and Mehdizadeh et al. (2015) observed changes in the pattern coordination only in specific joints couples after a speed variation of 45% and 20% respectively. Taken together, these results suggest that the response of coordination to changes in running speed is specific to the joint couple and the amount of speed variation. Furthermore, the changes in the percentage of time of each coordination pattern were only observed when the running speed increased, suggesting that the effect of speed on coordination does not only depend on the amount of variation, but also on the direction of that variation. Consequently, further investigations are needed to determine what amount and direction of speed variation is necessary to observe large changes in coordination pattern and which joint pairs are more influenced by running speed.

The analysis of the continuous coordination data during the running gait cycle allowed the identification of specific phases that were sensitive to variations in speed. These phases were: early stance, midstance and swing phases; differences were found in coordination in more than one joint couple, only in the early stance phase. These results highlight the important role of the early stance phase in readjustment of the lower limb with increases in speed. During the

first half of the stance the runner decelerates to absorb energy generated during landing (Schache et al., 2014). The differences observed in lower limb coordination suggest that when the foot contacts the ground, the recreational runners involved in the current study utilised a different energy absorption strategy dependent on the running speed. The changes in coordination were in the same direction in the three joint-coupling pairs where the differences were observed. A decrease in the percentage of running gait cycle in knee coordination accompanied by an increase in the percentage of running gait cycle in ankle coordination. These findings were consistent with the idea that ankle joint movement largely determines the ability to cushion (Phan et al., 2016) and push (Kulmala et al., 2016; Orendurff et al., 2018; Schache et al., 2014) during the running locomotion.

Variability has been considered as a measure of the ability to adapt to the constraints of a motor task, therefore greater variability may suggest greater adaptability (Preatoni et al., 2013). In the continuous recording of the coordination variability throughout the running stride, peaks of coordination variability were observed in the instants close to contact, midstance, toe-off or midswing. These instants coincided with relevant changes in the running technique, such as change of stance to swing or vice versa; changes from braking to propulsion during stance, midstance and midswing; the middle of the swing phase coincided with the midstance phase of the opposite foot. These peaks in coordination variability could indicate instances of overall instability due to the increased demands in comparison with the rest of the running cycle. These periods of rapid change in coordination variability could have important methodological consequences when examining the level of coordination variability in running and using average values obtained during longer periods may not accurately describe the nature of the coordination variability in running. Therefore, future research is necessary where coordination variability is determined via the analysis of the continuous signal rather than averaging values across specific phases in running.

The results showed that coordination variability was not sensitive to increases or decreases in running speed. These results are contrary to those reported by Bailey et al. (2018) who reported reductions in coordination variability in response to increased running speed. This discrepancy could be due to use the different coordination analysis techniques considering the present study used modified vector coding technique while Bailey et al. (2018) used continuous relative phase. Recent literature points out the advantages and disadvantages associated with each technique (Van Emmerik et al., 2013; Wheat & Glazier, 2006) and Miller et al. (2010) suggested that the comparison between studies that quantify coordination variability using different technique should be made with caution. Further studies are therefore needed to identify which analysis technique provides more useful information about running coordination variability.

Other limitations of this investigation are acknowledged. Most importantly, a treadmill was used to collect a sufficient number of strides and we acknowledge that this experimental condition could be considered a limitation of this study. The imposition of a constant velocity could remove the tendency to adapt to sudden changes in the environment and reduce the range of variability scores (Cazzola et al., 2016; Lindsay et al., 2014; Wheat et al., 2005). While it is common to use a treadmill to examine running coordination (Hafer, Brown, & Boyer, 2017; Rodrigues et al., 2015), this factor could be sufficient for the coordination values to differ from those obtained during overground running. Further studies that analyze the differences in coordination and coordination variability between running on a treadmill and overground are recommended in order to confirm or differentiate results between both conditions.

5. **Conclusions**

Overall, this study has demonstrated that a change in the running speed (±15%) was not sufficient enough stimulus to alter classification of coordination or coordination variability in recreational runners. Although they were found differences in the frequency of movement patterns mainly during the early stance. The low sensitivity of coordination and coordination variability to changes in speed suggests that coordination is generally stable in the range of training speeds used by runners. The analysis of continuous data on coordination and coordination variability has helped to increase knowledge and understanding of the control and organization of the running gait cycle. The results highlighted that the coordination pattern and the magnitude of the coordination variability depend on the temporal phase analysed. Throughout the whole running gait cycle, the pattern of coordination was continuously changing making it difficult to categorize coordination into a single type (antiphase, in-phase, proximal joint phase, and distal joint phase). Similar behaviour was found in the coordination variability. Peak values alternated with lower values making it difficult to determine the degree of movement variability in a specific runner. Therefore, it is difficult to determine whether a runner will increase or decrease his variability when faced with a new modified task.

6. **Funding sources**

References

Arampatzis, A., Brüggemann, G. P., & Metzler, V. (1999). The effect of speed on leg stiffness and joint kinetics in human running. *Journal of Biomechanics*. https://doi.org/10.1016/S0021-9290(99)00133-5

Bailey, J. P., Silvernail, J. F., Dufek, J. S., Navalta, J., & Mercer, J. A. (2018). Effects of treadmill running velocity on lower extremity coordination variability in healthy runners. *Human Movement Science*, *61*, 144–150. https://doi.org/10.1016/j.humov.2018.07.013

Berens, P. (2009). CircStat : A MATLAB toolbox for circular statistics. *Journal of Statistical Software*, *31*(10). https://doi.org/10.18637/jss.v031.i10

Bernstein, N. A. (1967). *The coordination and regulation of movements*. New York, NY: Pergamon.

Boyer, K. A., Silvernail, J. F., & Hamill, J. (2017). Age and sex influences on running mechanics and coordination variability. *Journal of Sports Sciences*, *35*(22), 2225–2231. https://doi.org/10.1080/02640414.2016.1265139

Brown, A. M., Zifchock, R. A., Hillstrom, H. J., Song, J., & Tucker, C. A. (2016). The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female runners with iliotibial band syndrome. *Clinical Biomechanics*, *39*, 84–90. https://doi.org/10.1016/j.clinbiomech.2016.09.012

Cazzola, D., Pavei, G., & Preatoni, E. (2016). Can coordination variability identify performance factors and skill level in competitive sport? The case of race walking. *Journal of Sport and Health Science*, *5*(1), 35–43. https://doi.org/10.1016/j.jshs.2015.11.005

Chan-Roper, M., Hunter, I., Myrer, J. W., Eggett, D. L., & Seeley, M. K. (2012). Kinematic changes during a marathon for fast and slow runners. *Journal of Sports Science and Medicine*, *11*(1), 77–82.

Chang, R., Van Emmerik, R., & Hamill, J. (2008). Quantifying rearfoot-forefoot coordination in human walking. *Journal of Biomechanics*, *41*(14), 3101–3105. https://doi.org/10.1016/j.jbiomech.2008.07.024

Cohen, J. (1977). The t test for means. In *Statistical Power Analysis for the Behavioral Sciences* (pp. 19–74). New York, NY: Academic Press.

Cole, G. K., Nigg, B. M., Ronsky, J. L., & Yeadon, M. R. (1993). Application of the joint coordinate system to three-dimensional joint attitude and movement representation: A standardization proposal. *Journal of Biomechanical Engineering*, *115*(4A), 344–349. https://doi.org/10.1115/1.2895496

Cunningham, T. J., Mullineaux, D. R., Noehren, B., Shapiro, R., & Uhl, T. L. (2014). Coupling angle variability in healthy and patellofemoral pain runners. *Clinical Biomechanics*, *29*(3), 317–322. https://doi.org/10.1016/j.clinbiomech.2013.12.008

DeLeo, A. T., Dierks, T. A., Ferber, R., & Davis, I. S. (2004). Lower extremity joint coupling during running: a current update. *Clinical Biomechanics*, *19*(10), 983–991. https://doi.org/10.1016/j.clinbiomech.2004.07.005

Dierks, T. A., & Davis, I. (2007). Discrete and continuous joint coupling relationships in

uninjured recreational runners. *Clinical Biomechanics*, *22*(5), 581–591. https://doi.org/10.1016/j.clinbiomech.2007.01.012

Divert, C., Baur, H., Mornieux, G., Mayer, F., & Belli, A. (2005). Stiffness adaptations in shod running. *Journal of Applied Biomechanics*. https://doi.org/10.1123/jab.21.4.311

Hafer, J. F., & Boyer, K. A. (2017). Variability of segment coordination using a vector coding technique: Reliability analysis for treadmill walking and running. *Gait and Posture*, *51*(1), 222–227. https://doi.org/10.1016/j.gaitpost.2016.11.004

Hafer, J. F., Brown, A. M., & Boyer, K. A. (2017). Exertion and pain do not alter coordination variability in runners with iliotibial band syndrome. *Clinical Biomechanics*, *47*, 73–78. https://doi.org/10.1016/j.clinbiomech.2017.06.006

Hafer, J. F., Silvernail, J. F., Hillstrom, H. J., & Boyer, K. A. (2016). Changes in coordination and its variability with an increase in running cadence. *Journal of Sports Sciences*, *34*(15), 1388–1395. https://doi.org/10.1080/02640414.2015.1112021

Hamill, J., Palmer, C., & Van Emmerik, R. E. A. (2012). Coordinative variability and overuse injury. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology*, *4*(1), 45. https://doi.org/10.1186/1758-2555-4-45

Hamill, J., Van Emmerik, R. E. A., Heiderscheit, B. C., & Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics*, *14*(5), 297–308. https://doi.org/10.1016/S0268-0033(98)90092-4

Hein, T., Schmeltzpfenning, T., Krauss, I., Maiwald, C., Horstmann, T., & Grau, S. (2012). Using the variability of continuous relative phase as a measure to discriminate between healthy and injured runners. *Human Movement Science*, *31*(3), 683–694. https://doi.org/10.1016/j.humov.2011.07.008

Helwig, N. E., Hong, S., Hsiao-Wecksler, E. T., & Polk, J. D. (2011). Methods to temporally align gait cycle data. *Journal of Biomechanics*, *44*(3), 561–566. https://doi.org/10.1016/j.jbiomech.2010.09.015

Hopkins, W. G. (2006). A scale of magnitudes for effect statistics. Retrieved from http://sportsci.org/resource/stats/index.html

Kuitunen, S., Komi, P. V, & Kyröläinen, H. (2002). Knee and ankle joint stiffness in sprint running. *Medicine & Science in Sports & Exercise*, *34*(1), 166–173. https://doi.org/10.1097/00005768-200201000-00025

Kulmala, J. P., Korhonen, M. T. T., Ruggiero, L., Kuitunen, S., Suominen, H., Heinonen, A., … Avela, J. (2016). Walking and running require greater effort from ankle than knee extensor muscles. *Medicine and Science in Sports and Exercise*, *48*(11), 2181–2189. https://doi.org/10.1249/MSS.0000000000001020

Kurz, M. J., Stergiou, N., Buzzi, U. H., & Georgoulis, A. D. (2005). The effect of anterior cruciate ligament recontruction on lower extremity relative phase dynamics during walking and running. *Knee Surgery, Sports Traumatology, Arthroscopy*, *13*(2), 107–115. https://doi.org/10.1007/s00167-004-0554-0

Lindsay, T. R., Noakes, T. D., & McGregor, S. J. (2014). Effect of treadmill versus overground running on the structure of variability of stride timing. *Perceptual & Motor Skills*, *118*(2),

331–346. https://doi.org/10.2466/30.26.PMS.118k18w8

McClay, I., & Manal, K. (1997). Coupling parameters in runners with normal and excessive pronation. *Journal of Applied Biomechanics*, *13*(1), 109–124.

Mehdizadeh, S., Arshi, A. R., & Davids, K. (2015). Quantifying coordination and coordination variability in backward versus forward running: Implications for control of motion. *Gait and Posture*, *42*(2), 172–177. https://doi.org/10.1016/j.gaitpost.2015.05.006

Miller, R. H., Chang, R., Baird, J. L., Van Emmerik, R. E. A., & Hamill, J. (2010). Variability in kinematic coupling assessed by vector coding and continuous relative phase. *Journal of Biomechanics*, *43*(13), 2554–2560. https://doi.org/10.1016/j.jbiomech.2010.05.014

Miller, R. H., Meardon, S. A., Derrick, T. R., & Gillette, J. C. (2008). Continuous relative phase variability during an exhaustive run in runners with a history of iliotibial band syndrome. *Journal of Applied Biomechanics*, *24*(3), 262–270.

Moore, I. S. (2016). Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sports Medicine*, *46*(6), 793–807. https://doi.org/10.1007/s40279-016-0474-4

Moore, I. S., Jones, A. M., & Dixon, S. J. (2012). Mechanisms for improved running economy in beginner runners. *Medicine and Science in Sports and Exercise*, *44*(9), 1756–1763. https://doi.org/10.1249/MSS.0b013e318255a727

Nakayama, Y., Kudo, K., & Ohtsuki, T. (2010). Variability and fluctuation in running gait cycle of trained runners and non-runners. *Gait and Posture*, *31*(3), 331–335. https://doi.org/10.1016/j.gaitpost.2009.12.003

Orendurff, M. S., Kobayashi, T., Tulchin-Francis, K., Tullock, A. M. H., Villarosa, C., Chan, C., & Strike, S. (2018). A little bit faster: Lower extremity joint kinematics and kinetics as recreational runners achieve faster speeds. *Journal of Biomechanics*, *71*, 167–175. https://doi.org/10.1016/j.jbiomech.2018.02.010

Osis, S. T., Hettinga, B. A., & Ferber, R. (2016). Predicting ground contact events for a continuum of gait types: An application of targeted machine learning using principal component analysis. *Gait and Posture*. https://doi.org/10.1016/j.gaitpost.2016.02.021

Osis, S. T., Hettinga, B. A., Leitch, J., & Ferber, R. (2014). Predicting timing of foot strike during running, independent of striking technique, using principal component analysis of joint angles. *Journal of Biomechanics*. https://doi.org/10.1016/j.jbiomech.2014.06.009

Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2015). Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *Journal of Biomechanics*. https://doi.org/10.1016/j.jbiomech.2015.02.051

Phan, X., Grisbrook, T. L., Wernli, K., Stearne, S. M., Davey, P., & Ng, L. (2016). Running quietly reduces ground reaction force and vertical loading rate and alters foot strike technique. *Journal of Sports Sciences*, *0414*(September), 1–7. https://doi.org/10.1080/02640414.2016.1227466

Pohl, M. B., Lloyd, C., & Ferber, R. (2010). Can the reliability of three-dimensional running kinematics be improved using functional joint methodology? *Gait and Posture*, *32*(4),

559–563. https://doi.org/10.1016/j.gaitpost.2010.07.020

Preatoni, E., Hamill, J., Harrison, A. J., Hayes, K., Van Emmerik, R. E. A., Wilson, C., & Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports Biomechanics*, *12*(2), 69–92. https://doi.org/10.1080/14763141.2012.738700

Rodrigues, P., Chang, R., TenBroek, T., Van Emmerik, R., & Hamill, J. (2015). Evaluating the coupling between foot pronation and tibial internal rotation continuously using vector coding. *Journal of Applied Biomechanics*, *31*(2), 88–94. https://doi.org/10.1123/JAB.2014-0067

Sadeghi, H., Allard, P., Shafie, K., Mathieu, P. A., Sadeghi, S., Prince, F., & Ramsay, J. (2000). Reduction of gait data variability using curve registration. *Gait and Posture*, *12*(3), 257–264.

Schache, A. G., Dorn, T. W., Williams, G. P., Brown, N. A. T., & Pandy, M. G. (2014). Lower-limb muscular strategies for increasing running speed. *Journal of Orthopaedic and Sports Physical Therapy*, *44*(10), 813–824. https://doi.org/10.2519/jospt.2014.5433

Seay, J. F., Van Emmerik, R. E. A., & Hamill, J. (2011). Low back pain status affects pelvis-trunk coordination and variability during walking and running. *Clinical Biomechanics*, *26*(6), 572–578. https://doi.org/10.1016/j.clinbiomech.2010.11.012

Seifert, L., Button, C., & Davids, K. (2013). Key properties of expert movement systems in sport: An ecological dynamics perspective. *Sports Medicine*, *43*(3), 167–178. https://doi.org/10.1007/s40279-012-0011-z

Silvernail, J. F., Boyer, K., Rohr, E., Brüggemann, G. P., & Hamill, J. (2015). Running mechanics and variability with aging. *Medicine and Science in Sports and Exercise*, *47*(10), 2175–2180. https://doi.org/10.1249/MSS.0000000000000633

Silvernail, J. F., Van Emmerik, R. E. A., Boyer, K., Busa, M. A., & Hamill, J. (2018). Comparisons of segment coordination: An investigation of vector coding. *Journal of Applied Biomechanics*, *34*(3), 226–231. https://doi.org/10.1123/jab.2017-0081

Söderkvist, I., & Wedin, P.-A. (1993). Determining the movements of the skeleton using well-configured markers. *Journal of Biomechanics*, *26*(12), 1473–1477. https://doi.org/10.1016/0021-9290(93)90098-Y

Van Emmerik, R. E. A., Miller, R. H., & Hamill, J. (2013). Dynamical systems analysis of coordination. In D. G. E. Robertson, G. E. Caldwell, J. Hamill, G. Kamen, & S. N. Whittlesey (Eds.), *Research Methods in Biomechanics* (pp. 291–315). Champaign, IL: Human Kinetics.

Wheat, J. S., Baltzopoulos, V., Milner, C. E., Bartlett, R. M., & Tsaopoulos, D. (2005). Coordination variability during overground, treadmill and treadmill-on-demand running. In Q. Wang (Ed.), *Proceedings of the 23th Conference of the International Society of Biomechanics in Sports* (pp. 781–784). Beijing.

Wheat, J. S., & Glazier, P. S. (2006). Measuring coordination and variability in coordination. In K. Davids, S. Bennett, & K. Newell (Eds.), *Movement System Variability* (pp. 167–182). Champaign, IL: Human Kinetics. Retrieved from http://www.humankinetics.com/products/all-products/movement-system-variability

Williams, K. R., & Cavanagh, P. R. (1987). Relationship between distance running mechanics, running economy, and performance. *Journal of Applied Physiology*. https://doi.org/10.1152/jappl.1987.63.3.1236
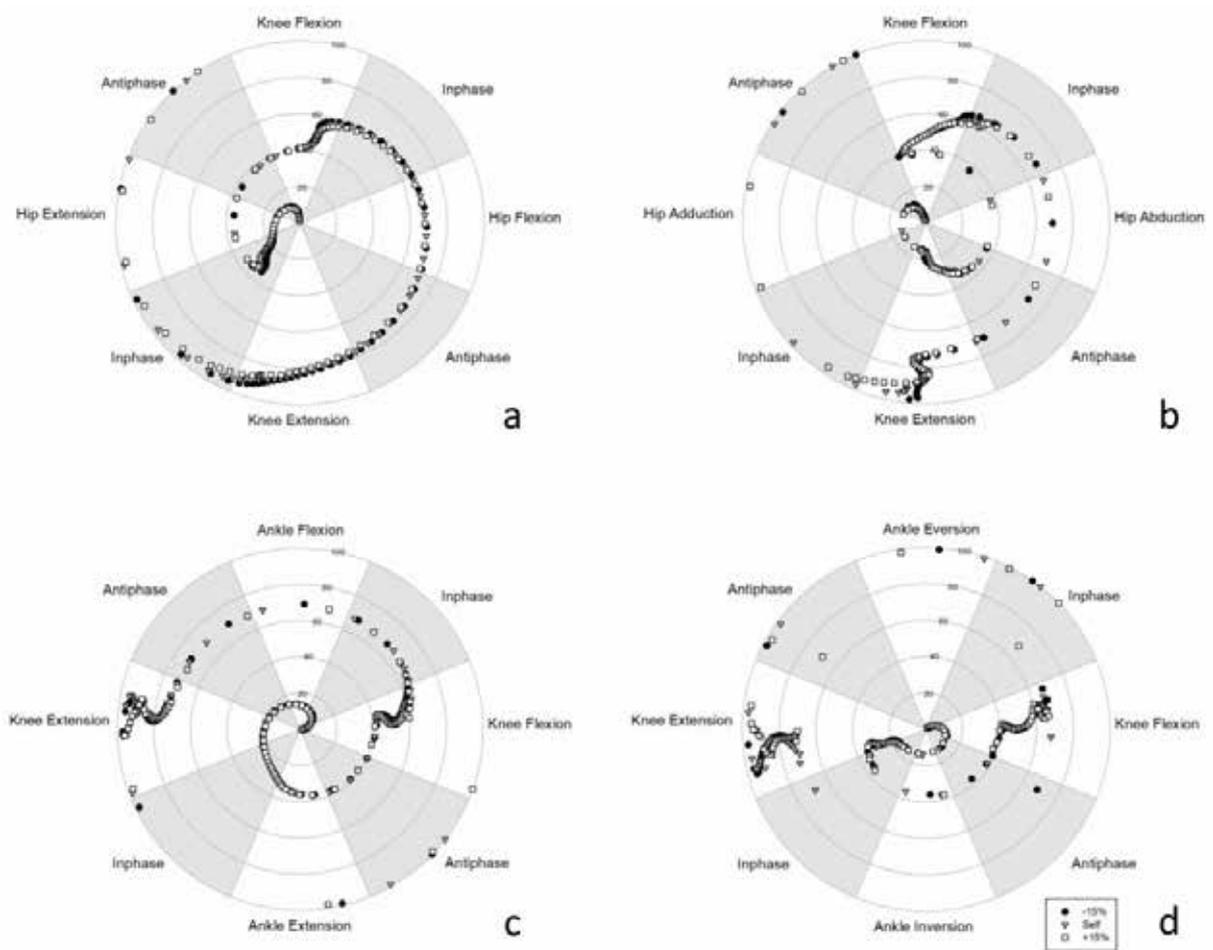
Figures

Figure 1. Vector coding angle plots for the three different speeds over running cycle: (a) HIPflex/ex-KNEEflex/ex, (b) HIPabd/ad-KNEEflex/ex, (c) KNEEflex/ex-ANKLEflex/ex, (d) KNEEflex/ex-ANKLEin/ev.
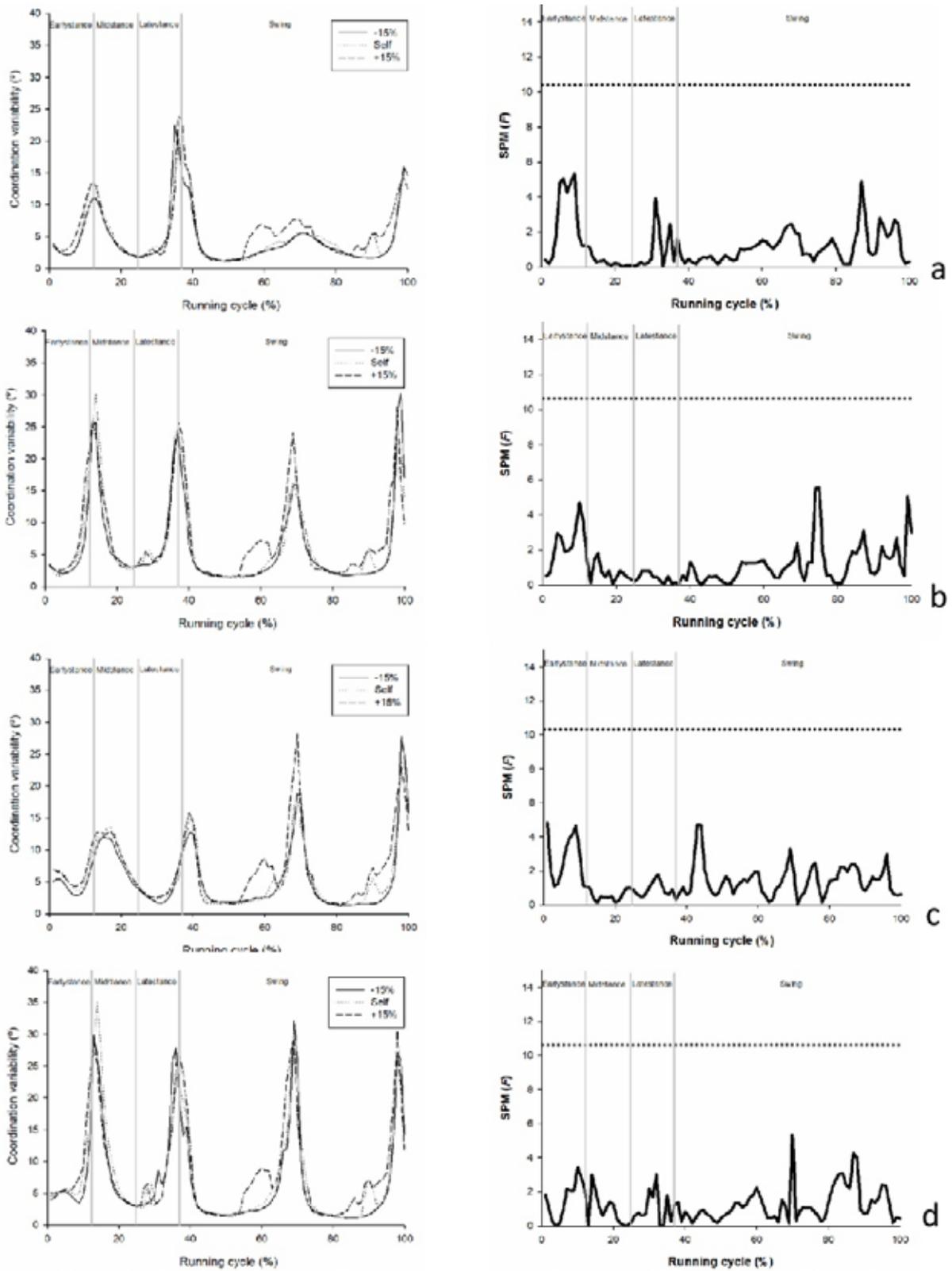
Figure 2. Vector coding variability for the three different speeds over running cycle (left) and F (SPM{F}) values at each normalized time point (right): (a) HIPflex/ex-KNEEflex/ex, (b) HIPabd/ad-KNEEflex/ex, (c) KNEEflex/ex-ANKLEflex/ex, (d) KNEEflex/ex-ANKLEin/ev.

22

These events are shown as an approximate average across three speeds for clarity of representation. The horizontal dotted line indicates the statistical significance level at P < .05.

Table 1. Speed comparisons across each phase of gait cycle for hip vs. knee couples: These are represented as binning percentages (means ± standard deviation)

	Early stance			Midstance			Late stance			Swing		
	Slow	Normal	Fast	Slow	Normal	Fast	Slow	Normal	Fast	Slow	Normal	Fast
HIPfe_KNEEfe												
In	/	/	/	9.8 ±0.8	9.6 ±1.1	9.8 ±1.6	9.7 ±2.3	9.7 ±2.7	9.9 ±2.9	12 ±2.6	12 ±2.4	12 ±2.5
Knee	8.8 ±1.6	8.3 ±1.8	7.8 ±1.7	/	/	/	1.0 ±1.7	1.2 ±2.1	0.9 ±2.2	37 ±3.5	37 ±3.5	36 ±4.3
Anti	2.9 ±1.3	3.3 ±1.4	3.4 ±1.0	0.3 ±0.6	0.3 ±0.5	0.3 ±0.6	0.5 ±0.5	0.3 ±0.5	0.2 ±0.4	8.8 ±1.9	8.6 ±1.9	8.5 ±2.1
Hip	0.3 ±0.5	0.4 ±0.7	0.8 ±1.3	2.8 ±0.7	3.1 ±1.0	2.9 ±1.3	0.8 ±1.1	0.8 ±0.8	0.9 ±0.6	6.4 ±1.6	6.4 ±2.0	6.8 ±1.9
HIPaa_KNEEfe												
In	/	/	0.1 ±0.3	1.6 ±1.7	1.8 ±1.5	1.5 ±1.6	0.6 ±0.7	0.3 ±0.6	0.5 ±0.8	5.9 ±3.8	7.0 ±2.8	7.7 ±2.6
Knee	6.8 ±3.1	5.9 ±3.9	**4.5 ±2.9^m**	8.9 ±2.0	8.5 ±2.1	8.3 ±3.1	5.9 ±4.2	6.2 ±4.1	6.2 ±3.7	52 ±4.1	51 ±3.8	49 ±4.9
Anti	5.1 ±3.0	5.9 ±3.7	7.2 ±2.8	1.4 ±1.9	1.8 ±2.4	1.9 ±3.5	4.7 ±3.7	5.2 ±4.2	4.8 ±3.8	3.8 ±1.9	4.3 ±1.9	5.2 ±3.3
Hip	0.1 ±0.3	0.2 ±0.6	0.2 ±0.6	1.1 ±0.6	1.0 ±0.6	1.2 ±0.8	0.8 ±0.8	0.4 ±0.5	0.7 ±0.7	2.4 ±1.0	2.2 ±1.3	2.5 ±1.1

Cell highlighting indicates the coordination pattern with the highest binning frequency. Bold values represent statistical differences from self-selected speed ($P < 0.05$). ^{m} indicates a moderate effect size. "/" indicates that test was not appropriate and therefore not run.

Table 2. Speed comparisons across each phase of gait cycle for knee vs. ankle couples: These are represented as binning percentages (means ± standard deviation)

	Early stance			Midstance			Late stance			Swing		
	Slow	Normal	Fast	Slow	Normal	Fast	Slow	Normal	Fast	Slow	Normal	Fast
KNEEfe_ANKLEfe												
In	6.0 ±1.4	5.8 ±1.5	6.6 ±2.1	3.7 ±1.0	3.5 ±1.1	**4.2 ±1.5ᵐ**	5.8 ±3.6	6.4 ±3.3	7.2 ±3.0	4.5 ±2.5	4.8 ±3.1	4.2 ±2.8
Ankle	0.5 ±0.7	0.6 ±1.0	**1.3 ±1.2ˡ**	2.2 ±0.8	2.5 ±0.8	2.3 ±0.9	5.6 ±3.3	4.8 ±2.7	3.8 ±2.1	2.8 ±1.0	2.3 ±0.8	2.5 ±1.1
Anti	0.7 ±0.9	0.8 ±1.0	0.8 ±1.0	2.9 ±0.6	3.2 ±0.6	2.8 ±0.6	0.4 ±0.9	0.4 ±0.9	0.5 ±1.0	5.5 ±1.8	5.2 ±2.0	4.7 ±2.5
Knee	4.8 ±1.3	4.7 ±1.9	3.3 ±1.6	4.2 ±0.9	3.8 ±0.9	3.8 ±1.2	0.2 ±0.6	0.5 ±1.2	0.5 ±1.4	51 ±3.7	52 ±3.9	**53 ±5.2ᵐ**
KNEEfe_ANKLEei												
In	4.4 ±1.9	4.8 ±1.9	5.4 ±2.1	3.8 ±3.6	4.3 ±2.8	5.2 ±3.6	3.5 ±3.9	3.2 ±3.7	3.0 ±3.8	5.3 ±2.6	5.1 ±3.1	6.6 ±3.8
Ankle	0.1 ±0.3	0.1 ±0.3	0.2 ±0.6	0.9 ±0.5	0.8 ±0.7	1.1 ±1.0	0.5 ±0.7	0.2 ±0.4	0.5 ±0.5	1.6 ±0.9	1.4 ±1.0	1.8 ±1.2
Anti	0.6 ±0.8	0.5 ±1.0	0.7 ±0.8	0.3 ±0.5	0.5 ±0.5	0.6 ±0.8	0.2 ±0.4	0.5 ±0.7	0.3 ±0.5	2.2 ±1.3	2.3 ±1.2	1.8 ±1.1
Knee	6.9 ±1.8	6.5 ±1.9	**5.8 ±1.9ᵐ**	7.9 ±3.7	7.4 ±3.0	6.1 ±3.6	7.8 ±4.3	8.0 ±3.9	8.2 ±3.9	55 ±3.4	55 ±4.5	54 ±4.9

1 Cell highlighting indicates the coordination pattern with the highest binning frequency. Bold values represent statistical differences from self-
2 selected speed (P < 0.05). [m, l] indicate moderate effect size and large effect sizes respectively. "/" indicates that test was not appropriate and
3 therefore not run.