Human Movement Science 64 (2019) 164–170

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Inter-joint coordination patterns differ between younger and older runners

Kathryn Harrison[a,*], Yong Ung Kwon[b], Adam Sima[c], Bhushan Thakkar[a], Gregory Crosswell[a], Jacqueline Morgan[a], D.S. Blaise Williams III[d]

[a] Department of Physical Therapy, Virginia Commonwealth University, Richmond, VA, United States
[b] Department of Human Health and Human Performance, Kean University, Union, NJ, United States
[c] Department of Biostatistics, Virginia Commonwealth University, Richmond, VA, United States
[d] Nike World Headquarters, Beaverton, OR, United States

A R T I C L E I N F O

Keywords:
Aging
Biomechanics
Hip
Knee
Ankle

A B S T R A C T

Older runners are at greater risk of certain running-related injuries. Previous work demonstrated that aging influences running biomechanics, and suggest a compensatory relation between changes in the proximal and distal joints. Previous comparisons of interjoint coordination strategies between young and older runners could potentially have missed relevant differences by averaging coordination measures across time.

Objective: To compare coordination strategies between male runners under the age of 30 to those over the age of 60.

Methods: Twelve young (22 ± 3 yrs, 1.80 ± 0.07 m, 78.0 ± 12.1 kg) and 12 older (63 ± 3 yrs, 1.78 ± 0.06 m, 73.2 ± 15.8 kg) male runners ran at 3.35 m/s on an instrumented treadmill. Ankle frontal plane, tibial transverse plane, knee sagittal plane, and hip frontal plane motion were measured. Inter-joint coordination was calculated using a modified vector coding technique. Coordination patterns and variability time series were compared between groups throughout stance using ANOVA for circular data.

Results: At the ankle, older runners use in-phase propulsion (inversion, tibia external rotation) pattern following midstance (46–47% stance) while young runners are still in an in-phase collapse pattern (eversion, tibia external rotation). In coordination of the knee and hip, older runners maintained an in-phase collapse pattern (knee flexion, hip adduction) approaching midstance (35–37% stance), while younger runners use an out of phase strategy (knee extension, hip adduction). In coordination of the ankle and hip in the frontal plane, older runners again maintained an in phase collapse pattern up to midstance (34–39% stance), while younger runners used an out of phase strategy (ankle inversion, hip adduction). Variability was similar between age groups.

Conclusion: Older runners appear to display altered coordination patterns during mid-stance, which may indicate protective biomechanical adaptations. These changes may also have implications for performance in older runners.

* Corresponding author at: 1200 East Broad Street, Box 980224, Richmond, VA 23298-0224, United States.
E-mail address: harrisonk3@vcu.edu (K. Harrison).

https://doi.org/10.1016/j.humov.2019.01.014
Received 11 May 2018; Received in revised form 14 January 2019; Accepted 16 January 2019
Available online 07 February 2019
0167-9457/

1. Introduction

Running is a popular recreational sport, with over 17 million participants in road races in 2015 in the United States. However, rate of participation peaks between the ages of 25–45, and thereafter declines steadily (Running, n.d.). A number of factors likely contribute to this decline, however pain is one of the most common barriers to exercise in elderly populations (Cohen-Mansfield, Marx, & Guralnik, 2003). Indeed, increased age has been associated with incidence of plantar fasciitis, Achilles tendinopathy and meniscal injuries in male runners (Taunton et al., 2002).

The cause of increased rates of certain injuries in older athletes has not been fully realized, and is surely multifactorial. However, changes in running mechanics likely play an important role. Older runners tend to have a lower preferred running velocity, with a shorter stride length and increased stride frequency compared to younger runners (Bus, 2003; Devita et al., 2016). Kinematic analyses at the joint level have produced conflicting results. Decreased joint excursions have been reported in older runners at the hip, knee, and ankle (Bus, 2003; Fukuchi & Duarte, 2008). However, others have reported no differences at the knee or ankle, and increased hip extension excursion in older runners (Silvernail, Boyer, Rohr, Brüggemann, & Hamill, 2015). The lack of differences in ankle and knee kinematics between age groups observed by Silvernail et al. (2015) may have been due the younger age range of their "older" group compare to other studies (Bus, 2003; Fukuchi & Duarte, 2008). However, the increased range of motion observed at the hip in runners aged 45–65 suggests a proximal shift in function begins as early as the 5th decade of life. Indeed, Devita et al. (2016) demonstrated progressive differences in running biomechanics from runners in their 20 s to those in their 80 s, suggesting small changes may exist which have been missed statistically. Assessment of joint coordination maybe more sensitive to shifts in biomechanical function between joints. Subtle changes at both joints may be imperceptible when measured in isolation, but together reveal meaningful differences in coordination strategy. It has been hypothesized that coordination between joints, as opposed to the mechanics of a single joint observed in isolation, may better explain running-related injury (Hamill, van Emmerik, Heiderscheit, & Li, 1999). Co-ordination of running in older individuals is not well understood. Kline and Blaise Williams (2015) found no change in the ratio of ankle eversion to tibia internal rotation between younger and older runners. However, because this calculation looks only at a single time point, changes in the relative motion of joints over the course of the entire stance phase may have been missed. Further, coordination patterns involving the hip and knee have not been investigated. Kinetic assessment of older runners demonstrates a reduction in the ability of the ankle to produce force (Devita et al., 2016), along with an increase in force production at the hip (Buddhadev & Martin, 2016; Franz & Kram, 2014), suggesting coordination between joints is affected by age.

Variability in coordination strategy within an individual is also an important consideration. Stride to stride fluctuations are proposed to allow for adaptability of a system to alterations in the demands of a task (Haken, Kelso, & Bunz, 1985). A further benefit of variability is that loads are distributed across different areas of tissue, reducing risk of repetitive stress injury. Prior research found that when variability is averaged across stance, there is no difference between young and old runners (Silvernail et al., 2015). By analyzing each third of stance separately, Boyer, Silvernail, and Hamill (2017) found differences in coordinative variability between younger and older females, but no age effect in males. However, the precise timing of variability relative to transition events is thought to be critical to healthy movement; Hamill et al. (1999) suggest that an increase in coordination variability immediately prior to transition points (eg. Mid-stance) is important to allow for successful switch to a new task (eg. loading vs. propulsion). Thus previous studies may have missed important temporal information regarding coordination variability by averaging over time.

Therefore, the purpose of this study was to the compare coordination patterns of the ankle, knee and hip, and their variability, between younger and older runners continuously throughout stance. Due to distal loss of force generation capacity and range of motion in older adults (Silvernail et al., 2015; Devita et al., 2016; Bus, 2003; Fukuchi & Duarte, 2008), we hypothesized older runners would demonstrate limited ankle motion relative to the knee and hip compared to young runners. We also hypothesized based on these limitations observed in older runners that they would display lower variability prior to midstance than younger runners.

2. Methods

2.1. Participants

A cross-sectional study design was employed. Twelve male runners between the ages of 18 and 30 (young: 22 ± 3 yrs, 1.80 ± 0.07 m, 78.0 ± 12.1 kg) and twelve male runners over the age of 60 (old: 63 ± 3 yrs, 1.78 ± 0.06 m, 73.2 ± 15.8 kg) were recruited from the local community via word of mouth. Power analysis was not performed as no previous work has reported standard deviation of vector coding coordination angles continuously through stance. Previous work using similar analysis methods performing a two-way comparison was able to detect significant differences with 4–13 participants per group (Rodrigues, Chang, TenBroek, van Emmerik, & Hamill, 2015). All participants were required to have run at least 10 km per week and been free of lower extremity or back injury for the previous 6 weeks. The Virginia Commonwealth University Institutional Review Board approved this study. All participants gave written informed consent prior to undergoing study procedures.

2.2. Gait analysis

All runners reported to a gait laboratory for testing. Neutral running shoes were provided for testing (New Balance, Boston, MA). Retroreflective markers were affixed to the lower extremity using a modified Cleveland Clinic model. Joint markers were placed bilaterally on the iliac crest, greater trochanter, medial and lateral knee, and medial and lateral malleolus. Rigid shells with clusters of 4 tracking markers were placed over the sacrum, thighs and shanks, and 3 tracking markers were attached to the heel counter of each shoe. A standing trial was collected to define joint centers and establish anthropometrics. Joint markers were then removed. Participants ran on an instrumented treadmill (Treadmetrix, Park City, Utah). The speed of the treadmill was gradually increased until the participant indicated they were at their preferred training pace. They ran at this pace for 1–2 min. Then the treadmill speed was gradually adjusted to a fixed pace of 3.35 m/s. Fixed pace data was used for this analysis, as speed may influence coordination (Chiu & Chou, 2012). When the participant indicated they were comfortable at that speed, a 20 s trial was collected using a 5-camera motion analysis system (Qualisys, Goteborg, Sweden) at 120 Hz. Force data was sampled at 1200 Hz.

2.3. Data processing

Visual 3D software (C-Motion, Germantown, MD) was used to process kinematic data. Marker trajectories were filtered using a 4th order dual pass Butterworth filter with a cut-off frequency of 10 Hz. Kinetic data were filtered using a critically damped filter with a cut-off frequency of 20 Hz. This type of filter was chosen for kinetic data in order to avoid under/overshoot at points of rapid transition, such as at impact during running (Robertson, Gordon, & Dowling, 2003). Force data was used to identify gait events (initial contact and toe-off) using a minimum vertical ground reaction force threshold of 20 N. Previous studies have focused on ankle eversion – tibial internal rotation coupling, as these motions function to absorb force during the loading phase of running, and thought to be related to injury (Ferber, Hreljac, & Kendall, 2009). Knee sagittal plane and hip frontal plane motion also help to absorb load during running. This is evidenced by a unimodal peak in joint position during stance phase, as runners "collapse" during the first half of stance (ankle eversion, tibia internal rotation, knee flexion, hip adduction) before reversing to a propulsive direction for the second half of stance (ankle inversion, tibia external rotation, knee extension, hip abduction). Further, hip adduction has been associated with injury (Noehren, Hamill, & Davis, 2013; Noehren, Davis, & Hamill, 2007), while knee flexion is associated with knee loading, and thus thought to be relevant to injury (Wille, Lenhart, Wang, Thelen, & Heiderscheit, 2014). For the current study, angles of the ankle in the frontal plane, tibia (ankle) in the transverse plane, knee in the sagittal plane and hip in the frontal plane were calculated during stance. Euler angle rotations were performed in the order X, Y, Z. Excursion from initial contact to peak angle was calculated for each motion in order to determine whether discrete single joint measures were different between age groups in this study population.

To quantify coordination, we chose to use a modified vector coding technique, since our aim was to quantify relative joint motion (Heiderscheit, Hamill, & van Emmerik, 2002). First, angle-angle plots were created. For each frame, the joint position of the distal joint/segment was plotted on the x-axis, and joint position of the proximal joint or segment was plotted on the y-axis. Positive joint positions indicate positions associated with collapse (i.e. ankle eversion, tibial internal rotation, knee flexion, hip adduction). Negative values indicate propulsion (ankle inversion, tibial external rotation, knee extension, hip abduction). Next, the angle of the vector connecting consecutive frames (coordination angle) was calculated as:

$$\Theta = \text{abs}[\tan^{-1}(\Delta p_{\text{proximal}}/\Delta p_{\text{distal}})]$$

where Δp is the change in joint angular position. This value was then adjusted such that if Δp for both joints was positive, the angle was between 0° and 90°, Δp_{distal} was negative while $\Delta p_{\text{proximal}}$ was positive the value was between 90° and 180°, Δp for both joints was negative the value was between 180° and 270°, and $\Delta p_{\text{proximal}}$ was negative while Δp_{distal} was positive the value was between 270° and 360° (Fig. 1).

Coordination relationships were calculated between adjacent joints (i.e. ankle frontal plane-tibial transverse plane, tibial transverse plane-knee sagittal plane, knee sagittal plane-hip frontal plane) as well as those in the same plane (i.e. ankle frontal plane-hip frontal plane). Coordination angles were calculated across stance phase, and interpolated to 101 data points each representing 1% stance. Due to the angular nature of the coordination measure, coordination data were analyzed using R: A Language and

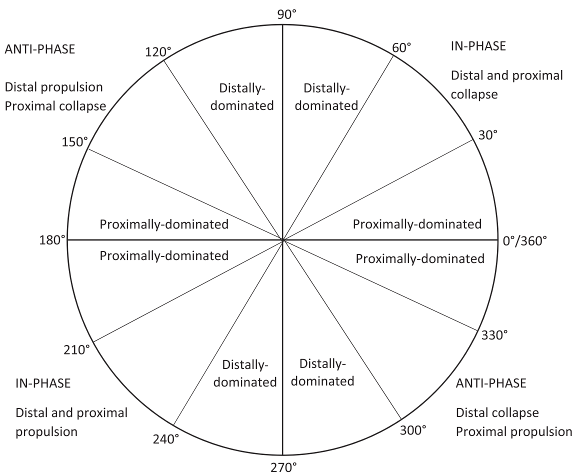

Fig. 1. Coordination angle interpretation.

environment for statistical computing (R Core Team, 2016), using the "circular" package (Agostinelli & Lund, 2013). The mean coordination pattern for each runner was created by calculating the circular mean of the coordination angle at each time point across all steps. Coordination variability was measured as the standard deviation of the coordination angle across all steps at each time point during stance.

2.4. Statistical analysis

Means and standard deviations (SD) of the joint excursions were calculated for each of the running groups and compared between groups using independent samples t-tests (α = 0.05). Comparisons of coordination pattern and coordination variability between young and older runners were performed using analysis of variance for circular data at each point during stance (Rodrigues et al., 2015). Since 4 joints pairs were examined, this resulted in 404 tests for coordination pattern and 404 test for coordination variability. Traditional family-wise error correction methods (e.g. Bonferroni) control the probability of Type I error (i.e. finding a statistically significant difference when in fact none exist), however they drastically increase the probability of Type II error (i.e. finding no statistically significant difference when in fact groups are different) when large scale multiple testing is performed. To account for the large number of tests in this study, the false discovery rate (FDR) was controlled according to the methods of Benjamini and Hochberg (1995). To apply this method, the acceptable FDR (q) was set to 0.05. The p-value for each test was assigned a rank (m) from lowest to highest (1…k), where k is the total number of tests. For each test, α was calculated as $\alpha = k/m{*}q$. All comparisons where the p-value is less than α were considered different. This method is considered favorable for large scale multiple testing as a small percentage of false discoveries among the total discoveries will not influence the overall conclusions of the study, while allowing for preservation of statistical power.

3. Results

Weekly mileage was not different between groups (young: M = 40 km/week, SD = 35; old: M = 28, SD = 16; p = 0.48). Young runners had a faster preferred pace than older runners (M = 3.33 m/s, SD = 0.48; M = 2.84, SD = 0.28, respectively; p = 0.001). No significant differences were found between groups for joint excursions, although older runners had nominally larger ankle frontal plane range of motion than young runners (p = 0.07; Table 1).

Differences in coordination pattern were observed during mid-stance (i.e. 30–50% stance, Fig. 2). At 46–47% stance, older runners used an in-phase propulsion ankle frontal plane-tibial transverse plane coordination pattern, while younger runners remained in an in-phase collapse pattern. From 35 to 37% stance, older runners used an in-phase collapse coordination pattern between knee sagittal plane and hip frontal plane motion, while younger runners used an anti-phase strategy, as they had reversed to propulsion with the hip while the ankle continued to collapse. Similarly, from 34 to 39% stance, older runners used an in-phase collapse coordination pattern between the ankle and hip in the frontal plane, while the younger runners had reversed with the hip such that they displayed an anti-phase coordination pattern.

Young and old runners did not show any statistically significant differences in the coordination variability after adjusting for multiple comparisons using the FDR method (Fig. 3). However, some potentially interesting discrepancies were apparent that warrant further exploration. It appears that younger runners had greater variability immediately prior to 40% stance (peak vertical ground reaction force), while older runners had greater variability immediately after 40% stance.

4. Discussion

The purpose of this study was to compare coordination between the ankle, knee and hip between young and old runners. Coordination patterns were similar between groups for the majority of stance, indicating that older runners are largely able to preserve running ability into their 60 s. However, it was observed that most coordination patterns differed between age groups for periods during mid-stance. This is the point where runners experience the greatest magnitude of loading, and thus is of particular concern. These findings were not reflected in comparison of single joint excursions.

At 46–47% stance, in coordination of ankle frontal and ankle transverse plane motion, older runners were moving in an in-phase propulsion pattern, while young runners maintained an in-phase collapse pattern. This indicates that older runners transitioned from collapse to propulsion earlier than the young at the ankle. This is supported by results from Fukuchi and Duarte (Fukuchi & Duarte, 2008), who reported shorter time to peak everions in older runners. Prolonged eversion has been associated with Achilles

Table 1
Excursions of selected motions for young and old runners from initial contact to peak angle during stance phase of running. Reported as mean(sd).

	Young	Old	p-value
Ankle frontal plane (°)	6.7 (3.6)	9.1 (2.5)	0.07
Tibia transverse plane (°)	13.5 (3.7)	16.1 (6.5)	0.24
Knee sagittal plane (°)	43.0 (5.9)	40.1 (5.9)	0.25
Hip frontal plane (°)	7.9 (4.2)	9.0 (4.1)	0.52

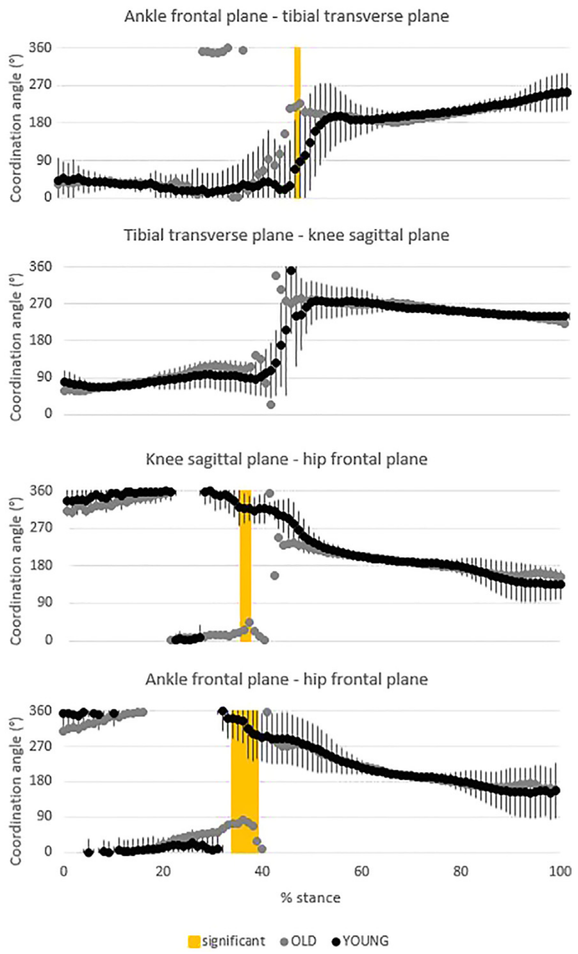

Fig. 2. Inter-joint coordination patterns during stance phase in young VS. older runners. Error bars represent group standard deviation of young runners.

tendinopathy (Ogbonmwan, Kumar, & Paton, 2018), thus the earlier reversal in older runners may represent an adaptation that has allowed this group of older runners to be injury free and stay active in the sport.

Coordination of both ankle frontal plane and knee sagittal plane motion with frontal plane hip motion, demonstrate that runners tend to initiate the shift from loading to propulsion at the proximal end, regardless of age group. The large gluteal muscles may be better able to generate the force needed to eccentrically halt the collapse and then propel the body. However, the fact that this transition occurred later in the older runners may be related to compromised distal function. It is well-documented that older people absorb less force with the ankle during locomotion than their younger counterparts (Devita et al., 2016), and this may be compensated by an increase in hip kinetics (Buddhadev & Martin, 2016; Franz & Kram, 2014). If this proximal shift occurs in the frontal plane as well, it may be that greater or prolonged hip adduction in older runners is necessary to absorb the force during loading.

It is also noteworthy that the young used an anti-phase coordination strategy in hip-knee and hip-ankle coordination, while the older runners used an in-phase coordination pattern during these periods. This is contrary to the idea that reversal of motion at each joint should occur in synchrony (Hamill, Bates, & Holt, 1992). The young runners in this study ran at a significantly faster preferred training pace, indicating they had greater running ability. Thus anti-phase motion may not be a sign of suboptimal movement. We offer an alternative hypothesis that anti-phase motion at peak vertical ground reaction force creates a stable system, taking advantage of passive resistance to more transfer force through the lower extremity. In agreement, Kiely and Collins (Kiely & Collins, 2016) suggest that "biotensegrity" – when tension and compression resistant tissues are organized in a specific configuration creating a self-stabilizing system - is pivotal in the coordination of human running. It is possible that protective adaptations in older runners (i.e. shorter period of pronation), require a trade-off with stability and efficiency.

The similar inter-joint coordination variability observed throughout stance between age groups in this study supports previous comparison of inter-segment coordination variability during gait among young adults, and active and sedentary older adults (Hafer & Boyer, 2018). That study reported that there were few differences in coordination variability between age groups, and these differences were largely eliminated in the older active group. The older runners in the current study would certainly be considered highly active, and this may have helped them preserve the ability to use a variety of movement strategies, allowing them to run

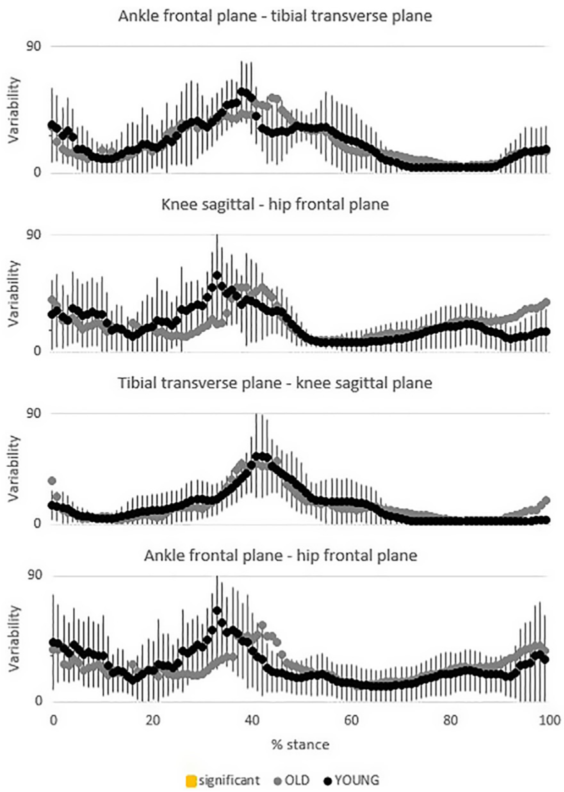

Fig. 3. Coordination variability during stance phase in young vs. older runners. Variability measures as intra-individual standard deviation of coordination angle. Error bars represent group standard deviation of variability in young runners.

successfully into older age. Future work should investigate the observation that older runners had lower coordination variability prior to mid-stance in 3 of 4 examined couples. Previous studies may have missed these differences by averaging variability over time, as older runners appear to have greater variability immediately following mid-stance. This may affect the ability of older runners effectively transition from loading to propulsion.

This study is limited by several factors. The sample size was based on previous work assessing coordination angles, thus it may not have been sufficient to detect differences in coordination variability. All participants were healthy, so we cannot say whether the observed differences in coordination influence risk of injury. Further, differences between young and old runners could be due to mileage or running experience, and not age (Boyer, Silvernail, & Hamill, 2014). Differences may also be related to experience running at the fixed pace used in this study, as the younger runners' preferred pace was much closer to the pace analyzed here. Since speed is known to affect coordination, it was important to compare runners at the same pace. The chosen pace was similar to the pace used in previous studies (Bus, 2003; Silvernail et al., 2015; Fukuchi & Duarte, 2008; Kline & Blaise Williams, 2015). Further, Bus et al. reported that the older runners in that study preferred to run at 3.34 m/s (Bus, 2003). The results could have been influenced by experience running on a treadmill, as most runners do most of their mileage over-ground. It was previously reported that treadmill and over-ground running were highly similar (overall trend symmetry 0.94) and that treadmill running was representative of over-ground running for most subjects (Fellin, Manal, & Davis, 2010). Finally, these results are only generalizable to male runners, as women and men may experience non-equivalent changes in running biomechanics with age (Boyer et al., 2017).

5. Conclusion

Older male displayed similar coordination patterns to young runners through the majority of stance. However, the older runners displayed different coordination pattern among the hip, knee and ankle during periods of mid-stance. This may reflect a protective adaptation that has allowed these athletes to continue to run into their 60 s. These differences may have implications for performance and injury in older runners.

Declarations of interest

None.

Funding

This study was supported by CTSA award No. UL1TR000058 from the National Center for Advancing Translational Sciences. Its contents are solely the responsibility of the authors and do not necessarily represent official views of the National Center for Advancing Translational Sciences or the National Institutes of Health.

References

Agostinelli, C., & Lund, U. (2013). *R Package "Circular": Circular Statistics (version 0.4-7)*.
Benjamini, Yoav, & Hochberg, Yosef (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B, Statistical Methodology, 57*(1), 289–300.
Boyer, Katherine A., Silvernail, Julia Freedman, & Hamill, Joseph (2017). The Role of Running Mileage on Coordination Patterns in Running. *Journal of Applied Biomechanics, 30*(5), 649–654.
Boyer, Katherine A., Silvernail, Julia Freedman, & Hamill, Joseph (2014). Age and sex influences on running mechanics and coordination variability. *Journal of Sports Sciences, 35*(22), 2225–2231.
Buddhadev, Harsh H., & Martin, Philip E. (2016). Effects of age and physical activity status on redistribution of joint work during walking. *Gait & Posture, 50*(October), 131–136.
Bus, Sicco A. (2003). Ground reaction forces and kinematics in distance running in older-aged men. *Medicine and Science in Sports and Exercise, 35*(7), 1167–1175.
Chiu, Shiu-Ling, & Chou, Li-Shan (2012). Effect of walking speed on inter-joint coordination differs between young and elderly adults. *Journal of Biomechanics, 45*(2), 275–280.
Cohen-Mansfield, Jiska, Marx, Marcia S., & Guralnik, Jack M. (2003). Motivators and barriers to exercise in an older community-dwelling population. *Journal of Aging and Physical Activity, 11*(2), 242–253.
Devita, Paul, Fellin, Rebecca E., Seay, Joseph F., Ip, Edward, Stavro, Nicole, & Messier, Stephen P. (2016). The relationships between age and running biomechanics. *Medicine and Science in Sports and Exercise, 48*(1), 98–106.
Fellin, Rebecca E., Manal, Kurt, & Davis, Irene S. (2010). Comparison of lower extremity kinematic curves during overground and treadmill running. *Journal of Applied Biomechanics, 26*(4), 407–414.
Ferber, Reed, Hreljac, Alan, & Kendall, Karen D. (2009). Suspected mechanisms in the cause of overuse running injuries: A clinical review. *Sports Health, 1*(3), 242–246.
Franz, Jason R., & Kram, Rodger (2014). Advanced age and the mechanics of uphill walking: A joint-level, inverse dynamic analysis. *Gait & Posture, 39*(1), 135–140.
Fukuchi, Reginaldo K., & Duarte, Marcos (2008). Comparison of three-dimensional lower extremity running kinematics of young adult and elderly runners. *Journal of Sports Sciences, 26*(13), 1447–1454.
Hafer, Jocelyn F., & Boyer, Katherine A. (2018). Age related differences in segment coordination and its variability during gait. *Gait & Posture, 62*(February), 92–98.
Haken, H., Kelso, Jas, & Bunz, H. (1985). A Theoretical model of phase transitions in human bimanual coordination. *Biological Cybernetics, 51*, 347–356.
Hamill, J., Bates, B. T., & Holt, K. G. (1992). Timing of lower extremity joint actions during treadmill running. *Medicine and Science in Sports and Exercise, 24*(7), 807–813.
Hamill, J., van Emmerik, R. E., Heiderscheit, B. C., & Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics, 14*(5), 297–308.
Heiderscheit, Bryan C., Hamill, Joseph, & van Emmerik, Richard E. A. (2002). Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. *Journal of Applied Biomechanics, 18*(2), 110–121.
Kiely, John, & Collins, David J. (2016). Uniqueness of human running coordination: The integration of modern and ancient evolutionary innovations. *Frontiers in Psychology, 7*(April), 262.
Kline, Paul W., & Blaise Williams, D. S., 3rd. (2015). Effects of normal aging on lower extremity loading and coordination during running in males and females. *International Journal of Sports Physical Therapy, 10*(6), 901–909.
Noehren, Brian, Davis, Irene, & Hamill, Joseph (2007). ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clinical Biomechanics, 22*(9), 951–956.
Noehren, Brian, Hamill, Joseph, & Davis, Irene (2013). Prospective evidence for a hip etiology in patellofemoral pain. *Medicine and Science in Sports and Exercise, 45*(6), 1120–1124.
Ogbonmwan, Ikponmwonsa, Kumar, Bhavesh D., & Paton, Bruce (2018). New lower-limb gait biomechanical characteristics in individuals with achilles tendinopathy: A systematic review update. *Gait & Posture, 62*(March), 146–156.
R Core Team (2016). *R: A language and environment for statistical computing*.
Robertson, D., Gordon, E., & Dowling, James J. (2003). Design and responses of butterworth and critically damped digital filters. *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 13*(6), 569–573.
Rodrigues, Pedro, Chang, Ryan, TenBroek, Trampas, van Emmerik, Richard, & Hamill, Joseph (2015). Evaluating the coupling between foot pronation and tibial internal rotation continuously using vector coding. *Journal of Applied Biomechanics, 31*(2), 88–94.
Running, Usa. n.d. "Research and Statistics." Running USA. Accessed August 23, 2017. http://www.runningusa.org/research.
Silvernail, Julia Freedman, Boyer, Katherine, Rohr, Eric, Brüggemann, Gert-Peter, & Hamill, Joseph (2015). Running mechanics and variability with aging. *Medicine and Science in Sports and Exercise, 47*(10), 2175–2180.
Taunton, J. E., Ryan, M. B., Clement, D. B., McKenzie, D. C., Lloyd-Smith, D. R., & Zumbo, B. D. (2002). A retrospective case-control analysis of 2002 running injuries. *British Journal of Sports Medicine, 36*(2), 95–101.
Wille, Christa M., Lenhart, Rachel L., Wang, Sijian, Thelen, Darryl G., & Heiderscheit, Bryan C. (2014). Ability of sagittal kinematic variables to estimate ground reaction forces and joint kinetics in running. *The Journal of Orthopaedic and Sports Physical Therapy, 44*(10), 825–830.