COORDINATION AND COORDINATION VARIABILITY DURING RUNNING
WITH RESPECT TO INTERNAL LOADING AND AGE

by

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Running is a largely popular and widely accessible form of exercise. However, running may pose risks to individuals due to its associations with high rates of injuries. Coordination between lower extremity joints and segments as well as coordination variability have linked to these running injuries. While mechanisms of injury are multifactorial, one theory suggests that reduced coordination variability may cause injury by increasing cumulative loading of soft tissue structures. This relationship may be important when assessing age, as prevalence of injuries differ between adolescents and adults. Therefore, this thesis aimed to 1) assess the relationship between coordination variability and loads in the Achilles tendon and patellofemoral joint during running 2) and evaluate differences in segmental coordination and variability between adolescent and collegiate runners. In Study 1, 64 healthy, adult runners ran on an instrumented treadmill while kinematics and kinetics were recorded. Coordination variability for knee-shank, knee-rearfoot, and shank-rearfoot couplings were calculated using vector coding. Achilles tendon and patellofemoral kinetics were calculated with musculoskeletal models. Surrogate variables were created for Achilles tendon and patellofemoral metrics using principal component analyses, and regressions were used to determine whether variability metrics predicted loading surrogates. One surrogate variable was created for Achilles loading, and lower knee-rearfoot variability predicted greater Achilles loading. Two surrogate variables were created for patellofemoral loading. Lower knee-rearfoot and knee-shank variability predicted greater peak patellofemoral loading, but no variability predicted cumulative patellofemoral loading. This suggests that a combination of low variability and large loads may be important for injury risk rather than cumulative loading. Study 2 assessed 21 competitive adolescent and 21 collegiate runners. Coordination variability was calculated using vector coding for various thigh, shank, and rearfoot couplings. Coordination patterns were analyzed using a binning frequency analysis. Adolescent and collegiate runners displayed different coordination patterns while running that primarily emerged from the transverse plane. Adolescent runners displayed greater coordination variability on average than collegiate runners. Combined with previous literature, this suggests a downward trend in coordination variability starting in adolescence and continuing through adulthood. In conclusion, coordination and its variability may be consequential in terms of injury mechanisms and different age populations.
CHAPTER ONE

INTRODUCTION

Running is one of the most popular recreational activities in the world due to its accessibility and associated health benefits. Unfortunately, running is also associated with a disproportionately large number of injuries, with up to three-quarters of runners sustaining an injury in any given year. These injuries are most often overuse in nature, stemming from repetitive loading of tissue over time. Traditionally, analyses have utilized discrete measures of motion like peak joint angles in an attempt to quantify potential injury development. However, a recent large-scale prospective study has shown that no discrete measures predicted whether runners became injured or not. Instead, recent literature has shifted to continuous measures like coordination that assess at how joint motion occurs over time. Coordination describes the ability for two joints or segments to come together and create a specific movement or reach an end goal. The ability to utilize multiple different patterns of coordination to produce the same end goal motion is known as coordination variability. Coordination variability allows for a system to adapt to external perturbations and gives flexibility to a system, and healthy motion inherently uses some amount of segment and joint coordination variability when performing movements like running.

Coordination variability has been linked to numerous running-related overuse injuries, with one of particular interest being patellofemoral pain (PFP). However, there are conflicting results on the exact association between coordination variability and these injuries. Early studies have shown that individuals with PFP exhibit smaller amounts of coordination variability during running than their healthy counterparts. Individuals with other injuries including lower back
pain\textsuperscript{10} and iliotibial band syndrome\textsuperscript{11} have also displayed less coordination variability during running than healthy individuals. More recent studies show the opposite relationship between coordination variability and injury, where injured runners instead displayed more coordination variability than healthy runners. This has been seen in a range of injured runners\textsuperscript{7} including PFP.\textsuperscript{9} Additionally, a recent prospective study suggests increased coordination variability may have implications for injury risk, as runners who displayed greater coordination variability went on to become injured.\textsuperscript{12} These discrepancies necessitate the exploration of specific mechanisms of injury that involve coordination variability.

It is possible that the relationship between coordination variability and injury incorporates internal loading of soft tissue structures. As previously stated, cumulative loading of tissues over time may lead to damage of those tissues and subsequently injury.\textsuperscript{13,14} For example, individuals with PFP demonstrate consistently greater patellofemoral (PF) joint stress than individuals without pain.\textsuperscript{15,16} Other injuries linked to internal loading include Achilles tendinopathy, specifically increased force and load transferred through the Achilles tendon.\textsuperscript{17,18} During running, some amount of loading is applied to these soft tissues on every stride. This internal loading accumulates over time and distance and may eventually exceed the tissue-specific loading capacity, thus resulting in running-related injury.\textsuperscript{14} It has been theorized that altered coordination variability may inform this mechanism of overuse injury.\textsuperscript{19} Specifically, reduced coordination variability during running indicates that joint or segment motion occurs in a similar manner on every stride. The consistency in motion across strides may lead to soft tissue structures being loaded similarly. In turn, this may increase the cumulative load of that tissue and lead to injury.\textsuperscript{19} Despite this theory being used in literature as a potential mechanism of injury, to
date, no literature has directly evaluated the relationship between coordination variability and internal loading to determine whether reduced variability does in fact lead to increased internal loading.

It is essential to resolve mechanisms of running-related injuries because these injuries often affect different populations more so than others. For example, older runners are more likely to develop Achilles tendinopathy than younger adults\(^3\) while adolescent runners often sustain more tibial stress injuries than adults.\(^3,4,20\) Coordination variability may lend one explanation to these differences in injury rates, as coordination patterns and coordination variability have also been shown to change with age. Older adults tend to display reduced variability compared to younger adults during running and walking.\(^{21-23}\) Older adults also exhibit different coordination patterns than younger adults, indicating that the older adults control joint motion differently. Despite the breadth of research evaluating coordination and coordination variability in older populations, little focus has been put on examining these measures in younger populations such as adolescents. Since coordination has been linked to running-related injuries as well as age, it may be beneficial to distinguish between mechanisms of injury for these different age ranges. The lack of connections created between coordination, coordination variability, internal loading, and adolescent age warrants investigation to further the knowledge of running-related injuries and mechanisms of these injuries. Therefore, the purpose of this thesis was twofold: 1) to assess the relationship between coordination variability and internal loading during running and 2) to compare coordination and coordination variability between adolescent and adult runners.
References


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CHAPTER TWO

REVIEW OF RELATED LITERATURE

Running Popularity and Prevalence of Injuries

Running is one of the most popular forms of physical activity in the world due to its wide accessibility and numerous health-related benefits.\(^1\,^2\) For the past decade, between 50 and 60 million individuals in the US have participated in recreational running or competitions at least once each year.\(^3\) Despite its popularity, running is plagued with injuries, with up to 79% of runners sustaining at least one running injury in any given year.\(^4\) In addition, over half of all runners report experiencing recurring or multiple different injuries.\(^5\,^6\) Most running injuries are overuse in nature, emerging from repetitive loading of the lower extremities over long periods of time. The most common overuse injuries seen in runners occur at the knee joint, accounting for between 25 and 30% of all running injuries according to recent studies.\(^5\,^7\) Specifically, patellofemoral pain (PFP) syndrome is the most common knee injury that affects runners.\(^5\,^8\) PFP is characterized by pain in the anterior portion of the knee joint and around the patella, specifically to retro- and peri-patellar areas.\(^9\) In general, PFP affects females more than males and is prevalent in adults of all ages.\(^9\) Another common site of injury for runners is the Achilles tendon (AT). Achilles tendinopathy may be debilitating long-term as individuals with Achilles tendinopathy are more likely to have ongoing orthopedic difficulties.\(^10\) Achilles tendinopathy generally occurs in the mid-portion of the Achilles tendon or at the insertion point of the tendon on the calcaneus.\(^11\) Achilles tendinopathy has previously been associated with age and a midfoot strike pattern, and males tend to develop Achilles tendinopathy more than females.\(^7\)
Lower Extremity Coordination and Running Injuries

Discrete Measures of Motion

Kinematic analyses have long been used to assess factors related to overuse running injuries. These analyses traditionally involve discrete measures of joint motion including peak angles, ranges of motion, and rotation velocities.\textsuperscript{7,12,13} There is a range of discrete measures that are associated with injury, including the ankle, knee, hip, and pelvis. At the ankle, runners who have sustained Achilles tendinopathy and medial tibial stress syndrome injuries display greater peak eversion and greater eversion velocity than healthy runners.\textsuperscript{14,15} At the knee, runners with chronic ankle instability have displayed less knee flexion at contact compared to healthy runners.\textsuperscript{16} Previous studies also show lower knee flexion velocity in runners with iliotibial band syndrome\textsuperscript{17} and lower peak knee flexion in runners with medial shin pain.\textsuperscript{18} At the hip, multiple studies have shown that individuals with PFP have greater peak hip adduction during running than healthy individuals.\textsuperscript{19–21} In addition, hip internal rotation is suggested to be larger in individuals with iliotibial band syndrome\textsuperscript{22} and medial shin pain\textsuperscript{18} but smaller in individuals with PFP\textsuperscript{23,24} than healthy individuals during running. Pelvis motion previously associated with overuse running injuries includes contralateral pelvic drop, where runners with PFP had greater pelvic drop than healthy runners.\textsuperscript{21}

Despite the evidence that suggests discrete measures may be used as predictors of running injuries, and because running-related overuse injuries are multifactorial, a growing body of literature is disputing these claims, and have instead shown that some injured populations may not have different peak kinematics than healthy controls that have previously been linked to running injuries.\textsuperscript{5,7,25,26} For example, one large-scale prospective study followed 300 runners
over a two-year period; contrary to previous literature, they found that no lower extremity kinematics were significant predictors of overuse injuries.\textsuperscript{5} Another large-scale retrospective study of 550 participants assessed factors related to running-related overuse injuries and came to similar conclusions, where no discrete kinematic variables were strongly associated with different injury locations.\textsuperscript{7} Other studies show differences in a minimal number of variables. One found that, while rearfoot eversion velocity was greater in prospectively injured collegiate runners compared to healthy runners, no hip or knee joint angles differed between the groups.\textsuperscript{25} The discrepancies in literature concerning these discrete measures merits additional further analysis of kinematics during running.

Continuous Measures of Motion: Coordination

In addition to the assessment of individual discrete kinematics, research has also considered how the discrete kinematics of different joints may occur relative to each other.\textsuperscript{27,28} Specifically, it is suggested that the timing between two peak joint angles may be indicative of performance or injury risk during running. Early examples include knee flexion and rearfoot eversion. Peak flexion and eversion were thought to happen at the same time during stance phase, and it was hypothesized that a disruption in this timing may lead to injury.\textsuperscript{27,28} With these results combined with conflicting evidence of discrete kinematics, research has moved to the evaluation of relative motion between joints or segments over entire gait cycles. The ability for two joints or segments to come together as a coordinative structure and create a specific movement or end goal is known as coordination.\textsuperscript{29,30} These coordinative structures are able to utilize multiple solutions, or coordination patterns, to create a movement. With a broad range of degrees of freedom comes inherent variability in the coordination of the system, known as
coordination variability. There are two interpretations of coordination variability. Variability in movement patterns may be viewed as the lack of coordinative structures and the inability to control redundant degrees of freedom. With the ability to utilize many different coordination patterns on different cycles of a movement, some variability within these patterns is inherent. Coordination variability, therefore, indicates the ability of the system to change and adapt to perturbations, giving some amount of flexibility to the system. Coordination variability may also describe the consistency of motion and whether similar patterns of coordination are used.

**Associations with Injury.** Multiple injuries have been associated with abnormal coordination and coordination variability. Seay et al. assessed coordination and coordination variability between the pelvis and trunk in runners with low back pain. Compared with healthy controls, individuals with low back pain displayed less coordination variability between the pelvis and trunk during running. Individuals with low back pain also displayed more in phase coordination patterns, which is not ideal for running gait. A secondary study by Seay assessed coordination between trunk flexion and trunk axial rotation. While coordination variability in the trunk bend-and-twist motion was not different in runners with low back pain than healthy runners, Seay did find abnormal coordination patterns with low back pain, where runners with low back pain displayed more in phase patterns.

Iliotibial band syndrome (ITBS) has also been assessed in relation to coordination. Miller et al. found that runners with a history of ITBS exhibited abnormal variability in multiple joint couplings, where variability was lower in tibial-rearfoot and thigh-rearfoot motion and greater in knee flexion-foot abduction. Hein et al. suggested contrary results, however. While not statistically significant, this study found that runners with ITBS displayed overall greater
coordination variability than healthy runners. These discrepancies may be explained by the couplings used. Miller et al. assessed a combination of joint and segment couplings whereas Hein et al. used only joint motion in assessments of coordination.

Like ITBS, studies that looked at PFP have also suggested conflicting results on its association with coordination and coordination variability. Hamill et al. assessed runners with symptomatic PFP and found that the injured runners overall displayed less coordination variability than healthy runners. This was only partially supported by Heiderscheit et al., who assessed runners with unilateral PFP compared to healthy runners as well as between the injured and uninjured legs of the PFP runners. They found less variability in the symptomatic PFP leg during heel strike than the unaffected leg, but no difference in variability over all of stance phase between healthy and injured runners. In contrast to these studies, Cunningham et al. found that coordination variability was overall greater in female recreational runners with PFP than in healthy recreational runners. As with ITBS, these differences may stem from the motion being evaluated. Hamill et al. and Heiderscheit et al. looked at inter-segmental couplings while Cunningham et al. looked at inter-joint couplings.

Recently, a prospective study has connected segmental coordination patterns and coordination variability to injury. This study followed 39 recreational runners for 6 months and found greater coordination variability during running in individuals who became injured over this period. Prospectively injured runners also displayed altered coordination patterns compared to healthy runners that were potentially unfavorable. It is possible, therefore, that coordination and coordination variability of different motion couplings affect the potential development of different running pathologies.
Methods of Analysis for Coordination and Coordination Variability

There are two main techniques to quantify coordination variability. One technique is called vector coding. This method is based directly off of the rotation of two joints or segments, where the two segments are plotted against each other, and the angle of the line created is calculated. Coordination variability is then defined as the variance of this angle over multiple cycles at each point in time.\textsuperscript{38} The second technique is called continuous relative phase (CRP), and involves phase relations of segments or joints. A phase relation quantifies the relationship between the angle and angular velocity of a joint, and coordination variability is defined as the difference in phase relations of two joints.\textsuperscript{30} Depending on the desired clinical relevance or measure sensitivity, it may be beneficial to utilize one of these techniques over the other. In addition to coordination variability, coordination patterns have been quantified by using binning frequency analyses. These analyses utilize relative motion plots between joints or segments and determine the time spent in specific coordination patterns depending on the angle of the line created between different time points.\textsuperscript{39,40} Together, these all give measures of coordination to aid in the interpretation of continuous motion.

Vector Coding

Early attempts to quantify coordination and coordination variability included angle-angle plots and chain encoding, which form the basis for vector coding techniques. Angle-angle plots were one of the original ways to assess how two segments or joints move in relation to one another.\textsuperscript{41} Angle-angle plots display one joint plotted on the horizontal axis and one plotted on the vertical axis, and the shape of the plot can be qualitatively assessed for its shape or size. While these plots are helpful to determine the consistency or variability of joint movements
between two cycles or individuals, the degree of variability is not quantified by visual inspection alone.

Whiting and Zernicke sought to quantify the analysis of angle-angle plots, suggesting the use of chain encoding. This method involves a series of elements that quantify the contour of the angle-angle plot based on the direction of the line formed between consecutive frames (Figure 1). Chain encoding has some limitations in terms of human movement, however. It is insensitive to time and therefore will not take into account how quickly a movement is performed. Sparrow et al. attempted to resolve this limitation by including the distance between the points of two time points in calculations, allowing for the distinction of similar coordination patterns with greater ranges of motion. With this technique, however, only two movement cycles can be compared at once, and the cycles must be the same length.

Two predominant methods were then presented as slight modifications to Sparrow’s vector coding technique. Both methods utilize angle-angle plots and calculate coordination as the orientation of a vector created between two consecutive time points from the right horizontal, defined as the coupling angle (Figure 2). However, there are slight variations in how this metric is calculated. Hamill, Haddad, and McDermott first determined the angle of the vector between adjacent points for each cycle, use these angles to calculate mean horizontal and vertical vector components across all cycles, and finally used these components to determine the mean coupling angle. In contrast, Tepavac and Field-Fote first determined the length of the vector between adjacent points for each cycle, used this length to calculate the sine and cosine of the angle, then used the mean sine and cosine over all cycles to calculate the mean coupling angle. The coupling angle is a circular variable defined from 0° to 360° and describes the patterns of
motion between two segments or joints, and coordination variability is defined as the circular
standard deviation of this coupling angle across cycles.\textsuperscript{35} Hamill’s modified vector coding
technique is currently the more preferred method of vector coding and is still widely utilized.

Vector coding is beneficial because it is relatively easy to interpret in a clinical setting.\textsuperscript{45–47} This is due to the fact that vector coding calculations are based solely on joint or segment
angles compared to other techniques of quantifying coordination. Additionally, joint and
segment angles do not need to be normalized, which allows for true spatial information to be
retained.\textsuperscript{38,45,47} However, vector coding is limited by not taking temporal information into
consideration.\textsuperscript{38,45} Only using spatial information without temporal information may limit the
sensitivity of the calculations. Finally, increased variability is seen with inflection points, where
there is a change in direction of joint rotation.\textsuperscript{35} The joints of interest have very little movement
for a brief time, creating a cluster of points in one area on an angle-angle plot. This proximity in
points will inherently increase the coordination variability as an artefact of vector coding
calculations.\textsuperscript{35,45}

Continuous Relative Phase

Continuous relative phase (CRP) stems from the basis of phase plane techniques. These
techniques were utilized to describe the motion of non-linear systems.\textsuperscript{48} Phase plane plots consist
of plotting velocity against displacement (Figure 3). Early studies in human locomotion
suggested that subjects moved limbs so that both limbs reached peak velocities and almost the
same time.\textsuperscript{48,49} Because of these observations, Kelso and colleagues\textsuperscript{48} attempted to quantify
interlimb coordination using phase relations. Kelso assessed voluntary oscillatory motion of the
index fingers and found that, as the velocity of out-of-phase motion increased, subjects abruptly
switched to an in-phase pattern. They proceeded to create a mathematical model to quantitatively express these qualitative phase relations. These models attempted to describe the phase shift between two oscillators with increasing frequency and highlighted the nonlinearity of these systems in terms of switching between coordinative structures.

Currently, CRP with locomotion is calculated using normalized values due to differences in range of motion magnitudes between different joints and segments. First, data are interpolated to a fixed number of points (i.e. 100% of stance). Displacement is then normalized based on maximum and minimum values over the cycle while velocity is normalized based on maximum magnitude over the cycle, creating a phase plot centered at 0 for both axes. Phase angles are then defined as the orientation of a vector between the origin and each data point from the right horizontal. CRP is then calculated as the difference between phase angles of two segments or joints, and CRP variability is defined as the standard deviation of the CRP across cycles. CRP is generally defined from either -180° to 180° or 0° to 360°. In both cases, CRP values close to 0° indicate in-phase motion whereas CRP values close to 180° indicate anti-phase motion. Additionally, values close to 360° and -180° are essentially the same as 0° and 180°, indicating in-phase motion and anti-phase motion, respectively.

Unlike vector coding, CRP utilizes both spatial and temporal information. This provides an additional layer of detail in the analysis and potentially allows for greater sensitivity to changes in coordination and its variability. However, one prominent limitation made with CRP is that joint motion is assumed to be sinusoidal. Because of this, some have suggested that CRP should not be used with non-sinusoidal motion. Another limitation of CRP is the difficulty of interpretation. It is conceptually difficult to apply phase relations to clinical
experiences, and therefore may not be ideal when clinically assessing pain or rehabilitation outcome metrics.38,43

Analyses of Coordination Patterns

Early studies seemed to assess coordination patterns in a more qualitative matter, focusing instead on the variability of coordination. This may have been due to the difficulty in the analysis and interpretation of circular data.53 Chang, van Emmerik, and Hamill39 was one of the first to establish meaningful labels for coordination patterns that could be quantitatively evaluated. These labels were based on vector coding calculations of coordination and included in-phase (segments moving equally in the same direction), anti-phase (segments moving equally in opposite directions), proximal dominancy (proximal segment dominating motion), and distal dominancy (distal segment dominating motion). With these labels, binning frequency analyses can then be performed, where the frequency of data points for each pattern is totaled, and differences between frequencies can be determined.39 These bins allowed Chang and colleagues39 to provide a more extensive picture of the coordination between rearfoot and forefoot segments during running.

When applying this technique to lumbar and pelvis motion, however, Needham, Naemi, and Chockalingam54 noted that the proximal and distal dominancy bins did not give information about the directionality of the segment motions. With the bins suggested by Chang,39 potentially harmful coordination patterns may be missed due to the inherent differences in range of motion magnitudes between segments. Therefore, Needham, Naemi, and Chockalingam40 developed a similar but more detailed binning frequency pattern that allowed for the detection of anti-phase motion with large differences in range of motion magnitudes. These bins suggested by Needham
and colleagues included in-phase with proximal dominancy, in-phase with distal dominancy, anti-phase with proximal dominancy, and anti-phase with distal dominancy. Each pattern was distinguished by directionality, with in-phase patterns being classified as positive rotation of both segments or negative rotation of both segments, and anti-phase patterns classified as positive proximal with negative distal segment rotations or negative proximal with positive distal segment rotations (Figure 4). This analysis allows for the differentiation of in-phase and anti-phase motion when one segment is moving much less relative to the other, and therefore may provide more detail in terms of pain and injury than the previously suggested model.

**Internal Loading and Running Injuries**

Multiple running injuries have been associated with internal tissue loading, including Achilles tendinopathy. Achilles tendinopathy often occurs due to the large and repetitive loads the AT is subjected to. Peak forces through the AT on any given step may be over six times body weight. The cause of these forces, however, is disputed in the literature. One potential mechanism includes rearfoot eversion, where some research has shown an association between Achilles tendinopathy and peak eversion angles, eversion velocity, and duration of eversion. This body of literature suggests that greater metrics related to eversion increase strain through the AT. However, a recent review found no effect of rearfoot eversion on AT injuries, and therefore continued research is warranted to resolve risk factors for Achilles tendinopathy and other AT injuries. AT force is often estimated using net ankle joint moments and AT moment arms based on studies that used magnetic resonance imaging (MRI). While this technique is often used for biomechanical analyses, it may not accurately estimate in vivo AT forces because it is not subject-specific and does not take into account co-contraction or
individual muscle contributions. Nevertheless, previous studies have shown similar AT force values when comparing this inverse dynamics-based calculation to other methods such as static optimization that do take into account co-contraction or muscle contributions.

Another running injury associated with internal loading is PFP. One of the most common metrics related to PFP is patellofemoral joint stress (PFJS). PFJS may be elevated with an increase in patellofemoral (PF) joint reaction force or a decrease in PF contact area. Some studies have found that individuals with PFP have similar PF joint reaction forces during walking but smaller contact areas than healthy controls, leading to increased PFJS. One study performed by Farrokhi, Keyak, and Powers reinforced the association between PFJS and PFP by using finite element modeling. This study found elevated hydrostatic pressure and shear stress across the PF joint.

PFJS is calculated as the PF joint reaction force divided by the PF joint contact area. PF joint reaction force is often calculated from a series of muscle force estimations, specifically for the quadriceps and co-contracting muscles like the hamstrings and gastrocnemius (Figure 5). Hamstring and gastrocnemius force estimations are often based on hip and ankle joint moments and utilize data collected from cadaveric or imaging studies to estimate muscle moment arms and cross-sectional areas. Similarly, the quadriceps force is calculated based on estimated quadriceps effective lever arms based on cadaveric studies, knee extensor moments, and the co-contraction of the knee flexors. The PF joint contact area can also be estimated using cadaveric or in vivo data from previously published literature as a function of knee flexion angles. Contact area, however, may also be measured using MRI images to estimate PF contact area values that are more subject-specific. One limitation of biomechanical
models such as this that estimate PFJS are that they are somewhat indirect and may not include a lot of subject-specific data. While this may make interpreting absolute PFJS values across studies somewhat difficult, these models may still be of use when evaluating relative PFJS values or PFJS within subjects.

**Relationship between Coordination and Internal Loading**

As previously described, both coordination and internal loading have been associated with running-related overuse injuries. However, no mechanism of injury has been directly assessed. One theory hypothesized on these mechanisms includes a direct relationship between coordination variability and cumulative loading. Specifically, a decrease in coordination variability may lead to certain soft tissue structures being loaded in a similar manner on every step during running. This repeated loading may increase the cumulative loading over time, exceeding the tissue’s loading capacity and thus leading to injury. For example, PF contact area is known to change with the degree of knee flexion. If coordination variability of segments around the knee joint is low, the degree of knee flexion will be similar on every step during running, PF contact area will be similar. In turn, loading transferred through the PF joint would be similar, thus exceeding the loading capacity of that portion of soft tissue in the PF joint and leading to injury. Interestingly, a recent prospective study challenged the notion that low amounts of variability lead to overuse injuries. This study performed by Desai and Gruber followed recreational runners and found that runners who prospectively became injured displayed greater coordination variability than uninjured runners. A recent systematic review supported Desai and Gruber’s findings, where injured runners had, on average, greater coordination variability than healthy control subjects. This discrepancy warrants further
investigation into mechanisms of running injuries and whether coordination variability does predict internal loading.

**Relationship between Coordination and Age**

While there is an ample amount of literature examining coordination and coordination variability in relation to older adults, there is little research exploring these measures in younger populations such as adolescents. With regard to adult populations, studies have shown that older adults have reduced coordination variability compared to young adults during walking and running.\(^{75–77}\) This may be harmful to older adults because reduced variability in this population has been associated with an increased risk of falling.\(^{78,79}\) Nevertheless, Silvernail et al.\(^{80}\) evaluated coordination variability in healthy older adult and younger adult runners and discovered similar amounts of coordination variability between the two cohorts. Additionally, Hafer and Boyer\(^{75}\) evaluated variability during running in active and sedentary older adults and found greater variability in active older adults during running for some segment couplings. The results of these studies suggest a positive influence of physical activity on coordination variability across the lifespan.

Coordination patterns are also altered during running in older adults compared to young adults. Hafer and Boyer\(^{75}\) evaluated intersegmental coordination to determine how older and younger adults control joint motion during running. The results suggested that older adults display different coordination patterns between pelvis-thigh and shank-rearfoot couplings than young adults, indicating that older adults control motion at the hip and ankle differently. Harrison and colleagues\(^{81}\) also discovered that older adult runners used different intersegmental coordination patterns than younger runners, again suggesting different control of motion of the
lower extremity joints. Harrison suggested that these differences in coordination may be protective adaptations for older runners that allow them to continue running into older adulthood. Alternatively, changes in coordination patterns may increase older adults’ risk of injury development, as some injuries like Achilles tendon injuries have been associated with increased age.

There is a general decline of coordination variability from young adulthood to older adulthood, but it is unclear whether a similar decline exists from adolescence to young adulthood, creating a downward trend of variability through the entirety of the lifespan, or whether adolescents actually exhibit less coordination variability than adults. It is well known that gross motor development continues through adolescents. Adolescents are yet to be proficient in some fundamental movement skills such as running and jumping. With this lack of proficiency, adolescents may naturally have increased coordination variability because they have not yet mastered the redundant degrees of freedom to create efficient movements. Alternatively, adolescents may display reduced coordination variability than adults due to an inherent lack of experience with these movements. Previous studies have shown that adults who are inexperienced with running display less coordination than experienced runners. Therefore, the association between experience and coordination variability may extend to adolescents, where the less experienced adolescent runners display less coordination variability than adult runners. Coordination and coordination variability in adolescents may be important to understand both performance and injury risk and therefore requires exploration.
Summary

Coordination and coordination variability have become valuable metrics to assess running injury risk as it has been association with multiple common overuse injuries. Common methods to quantify coordination include vector coding and continuous relative phase. Vector coding is a great method when attempting to apply coordination in a clinical setting whereas continuous relative phase allows for a more sensitive measure that include both spatial and temporal information. Despite coordination variability being associated with injury, the specific mechanism of injury has not been resolved. One theory for this mechanism includes internal loading, where reduced variability leads to increased cumulative loading of soft tissue, thus leading to injury. Coordination and coordination variability have also been associated with age, where older adults have reduced variability and different coordination patterns. It is unclear, however, how coordination differs between adolescents and adults. Resolving this relationship may shed additional light on risk of injury in adolescents. The following manuscripts, therefore, will examine the relationship between coordination variability and internal loading during running as well as the differences in coordination between adolescent and adult runners.
Figure 1. Whiting and Zernicke’s (1982) diagram of chain encoding used to quantify angle-angle plots. Estimated orientation of the line between two time points is based on nominal orientation classifications with a number assigned from 0 to 7.
Figure 2. Hamill, Haddad, and McDermott’s (2000) depiction of the coupling angle ($\gamma$), a metric used to define coordination based on angle-angle plots. Coupling angles are calculated as the orientation of the vector between two time points from the right horizontal.
Figure 3. Kelso et al.'s (1981) visualization of phase plane trajectories (velocity ($\dot{x}$) with respect to displacement ($x$)) compared to position-time functions. (a) depicts a fully cyclic phase relation. (b) depicts a decreasing phase relation. (c) depicts an increasing phase relation.
Figure 4. Needham, Naemi, and Chockalingam’s (2015) classification of coordination patterns based on coupling angles. Patterns are defined as either in-phase (segments rotate in the same direction) or anti-phase (segments rotate in opposite directions) as well as proximal dominancy (greater rotation in proximal segment than distal) or distal dominancy (greater rotation in distal segment than proximal).
Figure 5. Messier et al.’s (2011) schematic of estimated muscle forces used to calculate patellofemoral joint loads. Gastrocnemius and hamstrings forces from this model are often used to calculate patellofemoral joint contact forces and joint stress. $\alpha$, $\beta$, and $\Phi$ are the angles of force application relative to the tibia for the gastrocnemius, hamstrings, and quadriceps force, respectively.
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COORDINATION VARIABILITY PREDICTS ACHILLES TENDON AND PEAK PATELLOFEMORAL LOADING IN HEALTHY RUNNERS

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- [ ] Prepared for submission to a peer-reviewed journal
- ___ Officially submitted to a peer-reviewed journal
- ___ Accepted by a peer-reviewed journal
- ___ Published in a peer-reviewed journal
Abstract

**Background:** Despite the high prevalence of running-related overuse injuries, the driving factors of these injuries remain unclear. One theory on the mechanism of injury suggests that reduced coordination variability will lead to increased cumulative loading, thus leading to injury. However, this claim has not been evaluated. This study assessed whether runners with reduced coordination variability also displayed greater internal loading.

**Methods:** 64 healthy adult runners ran for 5 minutes on an instrumented treadmill while kinematics and kinetics were collected. Mean coordination variability over stance was calculated using vector coding for knee-shank, knee-rearfoot, and shank-rearfoot couplings. Achilles tendon (AT) and patellofemoral (PF) loading variables were calculated using musculoskeletal models. Principal component analyses were performed for AT and PF variables, and regressions were used to determine whether variability metrics predicted AT and PF surrogate variables.

**Findings:** One principal component was found for AT loading. Knee-rearfoot variability significantly predicted AT loading, where smaller variability was associated with greater loading. Two principal components were found for PF loading: “peak” and “cumulative” loading. Knee-rearfoot and knee-shank variability predicted “peak PF loading,” where reduced variability in both couplings was associated with greater “peak PF loading.” No variability metrics predicted “cumulative PF loading.”

**Interpretation:** Runners with reduced variability displayed greater AT and peak PF loading. While this does not support the claim that reduced variability leads to greater cumulative loading, the interaction between low variability and peak loads may be of consequence, creating
high frequencies of high loading during running. This may give insight into mechanisms of overuse injuries.

Introduction

Running is a tremendously popular form of physical activity. Unfortunately, running is also associated with high injury rates, with up to 79% of runners reporting some sort of running-related overuse injury (RROI) each year.\textsuperscript{1} The most commonly injured sites are the knee and the Achilles tendon, which include RROIs like patellofemoral pain syndrome (PFPS) and Achilles tendinopathy, respectively.\textsuperscript{2,3} One driving factor of these RROIs is increased tissue loading. Specifically, large amounts of loading to a tissue structure over time may surpass the load-specific capacity of that tissue, exceeding the injury threshold and thus producing an injury.\textsuperscript{4,5} Previous studies have shown increased patellofemoral (PF) contact forces and joint stress in individuals with PFPS\textsuperscript{6} while increased force through the Achilles tendon (AT) have been seen in individuals with Achilles tendinopathy than healthy individuals.\textsuperscript{7} Due to these relations, it is suggested that increased internal loading may be part of mechanisms of injury. However, RROIs are complex in nature, and using only one metric may not provide sufficient information on the mechanism of RROI development.

In conjunction with tissue loading, previous literature has attempted to quantify the risk for RROI development by using discrete measures of motion.\textsuperscript{5} However, some results have been inconclusive as some metrics like peak knee flexion or rearfoot eversion have been shown to be similar between injured and healthy subjects.\textsuperscript{2} More recently, focus has shifted to measures of relative motion between segments and how this motion is coordinated across multiple gait cycles.\textsuperscript{8-12} This relative motion is known as coordination, and describes the ability for segments
or joints to come together in a coordinative structure to create a specific movement. Variability of movement within this system to reach a specific end goal is defined as coordination variability, and it allows for some flexibility of the system to adapt to perturbations. Recent studies have found altered coordination variability in multiple injured running populations. Coordination variability has been shown to be lower in runners with patellofemoral pain, low back pain, and iliotibial band syndrome than healthy runners. However, other prospective studies suggest coordination variability is overall greater in subjects with a range of RROIs than healthy subjects. These discrepancies in the literature warrant further research into the mechanism of RROIs and the relationship between coordination variability and RROI development.

Previous studies have hypothesized that the mechanism of RROIs involve both coordination variability and internal loading. Specifically, a reduction in variability may lead to specific tissues being loaded in a similar fashion during every gait cycle. In turn, this may increase the cumulative load of that joint. This increased cumulative loading may then exceed the loading capacity of that tissue and injury threshold, thus leading to RROIs. For example, if variability between the thigh and shank motion is low during running, a similar amount of knee flexion is occurring during subsequent steps of running gait. It is known that PF contact area changes with knee flexion, and therefore, loads may be applied to the same area of the PF joint. Despite previous studies utilizing this hypothesis in injured populations as a potential mechanism of RROIs, to date, no studies have assessed whether decreased variability actually leads to increased internal loading in healthy running populations. Therefore, the purpose of this study was to determine whether runners with reduced coordination variability also displayed greater
AT and PF loading. It was hypothesized that runners with decreased coordination variability would display in greater AT and PF loads while running.

Methods

Participants

Sixty-six individuals participated in this study (sex: 36 M/28 F, age: 25.23 ± 8.06 years, height: 1.74 ± 0.08 m, mass: 64.35 ± 11.36 kg, easy run training pace = 3.20 ± 0.46 m/s). Participants were recruited from the local community and collegiate track team between August 2018 and November 2019. Inclusion criteria included running for at least 15 miles per week, no history of lower extremity surgery, and no lower extremity injuries in the three months prior to testing. All protocols were approved by the Institutional Review Board and participants provided written consent prior to participation in the study.

Protocol

Participants warmed up for five minutes at a self-selected pace. They then ran for five minutes at a self-selected pace which matched their regular easy run training pace. Lower extremity kinematics and kinetics were recorded using a 6-camera motion capture system sampling at 250 Hz (Motion Analysis, Santa Rosa, CA, USA) and an instrumented treadmill sampling at 1000 Hz (Treadmetrix, Park City, UT, USA), respectively. Reflective markers were placed on the anterior and posterior superior iliac spines, medial and lateral femoral epicondyles, medial and lateral malleoli, and head of the second metatarsal. Additional tracking markers were placed on the iliac crests, tibial tuberosity, and base of the fifth metatarsal. Three markers were carefully placed on the heel counter, two vertically and one on the lateral side, and 4-marker
rigid-body clusters were placed on the lateral thigh and shank segments and secured with elastic wrap.

**Data Reduction and Analysis**

Marker trajectories and ground reaction forces were exported to Visual 3D (C-Motion, Germantown, MD, USA) where they were filtered using 4th order, zero-lag Butterworth filters with 8 and 50 Hz cutoff frequencies, respectively. Heel strike and toe off events were determined using a 50 N threshold of the vertical ground reaction force, and twenty consecutive stance phases were extracted for analysis. Each stance phase was normalized to 100% of stance. Hip, knee, and ankle joint angles were calculated using an XYZ Cardan rotation sequence corresponding to flexion/extension, abduction/adduction, and axial rotation. Shank segment angles were calculated with respect to the lab coordinate system using a YXZ Cardan rotation sequence corresponding to flexion/extension, abduction/adduction, and axial rotation. Joint moments at the hip, knee, and ankle were calculated using inverse dynamics, and expressed as internal moments in the coordinate system of the distal segment.14

AT and PF metrics were calculated using previously described musculoskeletal models and custom MATLAB code (MathWorks, Natick, MA, USA).14 AT forces were calculated using the ankle plantar flexor moments calculated from inverse dynamics and Achilles moment arms, which were determined as a function of ankle joint angles.15 Peak plantar flexor moment, peak AT force, peak AT loading rate, impulse per step, and cumulative impulse per km of running were then calculated. PF kinetics were calculated with co-contraction of the gastrocnemius and hamstrings muscles taken into account.14 Briefly, AT forces were portioned into gastrocnemius and soleus forces based on their respective physiologic cross-sectional areas.16 Hamstring forces
were calculated using the hip extensor moments from inverse dynamics, hamstring and gluteus maximus physiologic cross-sectional areas, and sex-specific hamstring and gluteus maximus moment arms as a function of hip angle. Knee flexor moments created by the gastrocnemius and hamstring muscles were based on their respective knee flexion moment arms. To account for co-contraction, this knee flexor moment was added to the net knee extensor moment calculated from inverse dynamics, and quadriceps forces were determined using the quadriceps effective lever arm, which varied with knee angle. PFCF was then calculated as a function of quadriceps force and knee flexion, and PFJS was calculated using PFCF and contact area.

Peak knee extensor moment, peak PFCF and PFJS, PF loading rate, impulse, and impulse per km were then calculated.

Coordination variability was calculated using a modified vector coding technique and custom MATLAB code (MATLAB, MathWorks, Natick, MA, USA). Segment couplings of interest included knee flexion with shank internal rotation (knee-shank), knee flexion with rearfoot eversion (knee-rearfoot), and shank internal rotation with rearfoot eversion (shank-rearfoot). These couplings were chosen due to the potential to increase loading at the knee joint and previous links with running injuries. Relative motion plots for two segments were created for each gait cycle. Coupling angles were then calculated as the orientation of a vector created by consecutive time points from the right horizontal. Variability was defined for each set of consecutive time points as the circular standard deviation across gait cycles. Mean variability was then determined across participants for total stance phase.
Statistical Analysis

Data were first checked for outliers using box and whisker plots and Cook’s distances. Two outliers were found and discarded, giving a final sample size of 64. Principal component analyses (PCA) was used to reduce the highly correlated AT and PF loading measures into orthogonal dimensions. Principal components were determined by spectral decomposition of the correlation matrix, and where more than one component was extracted, were subjected to variance maximizing rotations. Principal components with eigen values greater than one were retained for subsequent interpretation. Since these factor scores are dependent on sample data, surrogate variables for each factor were created based on factor loadings.\(^{24}\) Linear regressions between surrogate values and PC factor scores were computed to ensure that each surrogate accurately represented the PC factor. Due to the curvature of the data, curve estimations were performed, and quadratic terms were added into the model. Multiple regressions with linear and quadratic terms and stepwise variable selection were then performed to determine whether mean variability for knee-shank, knee-rearfoot, and shank-rearfoot couplings predicted AT or PF loading surrogate variables. Statistical analyses were performed using SPSS v26.0.0.1 (IBM Corp., Armonk, NY, USA).

Results

Achilles Tendon Loading

Mean variability, AT, and PF metrics are shown in Table 1. PCA factor loadings are shown in Table 2. For Achilles tendon metrics, one principal component with an eigen value of \(\lambda_1 = 4.24\) was extracted. This component accounted for 84.8% of the overall variance in Achilles loading metrics. Peak plantar flexor moment, peak AT force, peak AT loading rate, impulse per
step, and cumulative impulse all loaded strongly onto this component, which was labeled as “Achilles load” (Table 2). The mean of these five variables was calculated as a surrogate for this component, and regression of surrogate scores versus factor scores showed this surrogate accurately captured this factor. “Achilles load” was significantly predicted by knee-rearfoot variability ($R^2 = 0.088$, $p = 0.01$, Figure 2). “Achilles load” was not predicted by any second-order terms. For every one-degree increase in knee-rearfoot variability, “AT load” decreased by 5.61 units ($p = 0.01, 95\% \text{ CI } -9.83 – -1.39$).

**Patellofemoral Joint Loading**

For PF metrics two principal components with eigen values of $\lambda_1 = 4.11$ and $\lambda_2 = 1.34$ were extracted. Together these two components accounted for 90.8% of the overall variance. Peak knee extensor moment, peak PFCF, PFCF loading rate, and peak PFJS all loaded strongly onto the first principal component, which was labeled as “peak PF loads” (Table 2). The mean of these four variables were calculated to create surrogate values for this component. A regression creates for surrogate values with respect to “peak PF loads” factor scores showed that the surrogate values did accurately capture the “peak PF loads” factor. “Peak PF loads” were significantly predicted by a model containing knee-rearfoot variability and knee-shank variability ($R^2 = 0.285$, $p < 0.01$, Figure 1). “Peak PF loads” were not predicted by any second-order terms. For every one-degree increase in knee-rearfoot variability, “peak PF loads” decreased by 4.79 after accounting for knee-shank variability ($p = 0.003, 95\% \text{ CI } -7.89 – -1.70$). For every one-degree increase in knee-shank variability, “peak PF loads” decreased by 4.15 units after accounting for knee-rearfoot variability ($p = 0.016, 95\% \text{ CI } -7.51 – -0.80$).
PF impulse per step and cumulative impulse per km both loaded onto the second principal component, which was labeled as “cumulative PF load” (Table 2). The mean of these two variables was calculated as a surrogate for this component, and regression of the “cumulative PF load” surrogate and component two factor scores showed this surrogate accurately captured this factor. “Cumulative PF loads” were not predicted by any variability metrics ($R^2 = 0.01$, $p = 0.36$).

Discussion

The purpose of this study was to determine whether coordination variability and loading of the AT and PF joint were associated during running. It was hypothesized that runners with lower coordination variability would also display greater AT and PF loads. The results partially supported the hypothesis, as “Achilles load” and “peak PF loads” were greater with smaller variability metrics. Contrarily, “cumulative PF loads” were not predicted by any variability metrics. This also does not support the theorized mechanism of injury described in previous literature that states reduced variability may lead to increased loading over time.9 These results suggest that the mechanism in which coordination variability is linked to injury may be through an increase in peak internal loading during running, and that cumulative loading of the patellofemoral joint may not be as important to injury as previously speculated.25

AT loading metrics were generally in line with or slightly higher than previously reported values.14,26,27 This is expected as AT forces and loading rates tend to be greater during treadmill running, as performed in this study, compared to overground running.14 Most PF loading metrics were also in line with previous literature.14,28 However, PF impulse per km values were somewhat lower than what has been established.14,28 Smaller cumulative impulse values have
been shown with forefoot strike patterns as well as shorter stride lengths.\textsuperscript{28} While not specifically evaluated in this study, more runners in this study may have had forefoot strike patterns than rearfoot strike patterns. Additionally, cumulative PF joint loading may be higher at slower running velocities.\textsuperscript{29} This may account for the differences in cumulative PF loading, as the average running speed in the current study is higher than previous studies assessing loading.\textsuperscript{14,28} Coordination variability metrics were overall smaller than reported values.\textsuperscript{11,30} It is possible that running experience influenced these values, as previous literature shows less variability in runners with less than two years of experience than in runners with over 10 years of experience.\textsuperscript{31} The majority of runners in the current study had less than 10 years of running experience, with some as little as one year, which potentially had an effect on coordination variability. Nevertheless, overall trends of coordination through stance phase are similar to those seen in literature,\textsuperscript{11} and therefore may be a product of this sample.

**Achilles Tendon Loading**

One component was extracted from the principal component analysis of AT loading. This indicates that peak and cumulative loading provide similar information for the AT. Loading of the AT was predicted only by knee-rearfoot variability. Despite weak evidence suggesting that discrete knee kinematics are associated with Achilles tendinopathy,\textsuperscript{32} these results suggest that the knee and rearfoot are mechanically linked and that continuous motion at both the proximal and distal joints of the AT are important to its loading. The association between low knee-rearfoot variability and high AT loading suggests that forces may be transmitted through the AT and lower extremity repeatedly in similar fashion during running. However, further investigation is warranted to determine if knee-rearfoot coordination and variability is related to Achilles
tendinopathy. Shank-rearfoot variability was not a predictor of AT loading, which was unexpected, as coordination variability between the shank and rearfoot have been previously linked to runners with a history of AT rupture or tendinopathy.\textsuperscript{33,34} Interestingly, the relationship found between knee-rearfoot variability and AT loading was linear, with no significant quadratic terms predicting AT loading. While there seems to be a potential non-linear relationship, it may also be a skew in distribution of the AT loading surrogate variable. Thus, further research may be necessary to determine whether this relationship is indeed non-linear.

**Peak Patellofemoral Loading**

Peak PT loading was predicted by both knee-shank and knee-rearfoot variability. The current theory on the relationship between coordination variability and internal loading suggests that reduced variability leads to increased loading over time because these loads are transferred through joints in similar locations during each stride. This then exceeds the load capacity of that tissue, resulting in injury.\textsuperscript{4,5} The present results, however, suggest that it is not cumulative loading, but peak loading, that is associated with reduced variability. RROIs often occur when specific combinations of stress and frequency are applied to a tissue; this may mean large amounts of stress over short periods of time or small amounts of stress over more time.\textsuperscript{5} When variability is reduced, tissue structures get repeatedly loaded in a similar manner. In other words, the frequency of loading within the tissue increases. Therefore, the combination of high loads at a high frequency due to reduced variability may be the cause of overuse injuries rather than an increase in cumulative loading. Like AT loading, peak PF loading was predicted only by linear relationships with variability despite potential non-linear relationships between the metrics. These trends warrant further investigation into non-linear relationships of variability and loading.
Cumulative Patellofemoral Loading

The lack of statistical significance between coordination variability and cumulative PF loading may be clinically significant. In runners with low variability, the PF joint may be adapted to accommodate the high peak loads. In contrast, individuals with greater variability displayed similar amounts of loading at the PF joint per kilometer to those with less variability, but the large variability seen in these runners may suggest that the stress in the PF joint changes slightly on every step. The abnormal placement of stress on the PF joint may then drive the development of PF pain.\textsuperscript{4,35} This theory may be supported by a recent systematic review as well as a prospective study that give evidence that injured runners display greater amounts of coordination variability than runners who are healthy.\textsuperscript{11,36}

Driving Factors of Patellofemoral Loading

Overall, the relationship between coordination variability and PF loading seems to be driven by motion at the knee, as expected and evidenced with both knee-shank and knee-rearfoot couplings predicting PF peak loading. Motion of the knee, shank, and rearfoot are mechanically linked, and therefore, motion of the shank and rearfoot subsequently affect the knee joint, especially in closed chain activities such as running.\textsuperscript{35,37} It has previously been suggested that abnormal coordination of the rearfoot and knee joints may increase stress placed on soft tissue structures of the knee.\textsuperscript{37} In light of the present study, it is possible that runners who experienced high PF peak loading and low amounts of coordination variability spent more time in abnormal, antiphase coordination patterns more than the runners with higher coordination variability. However, additional research is needed to solidify this relationship.
Limitations

There are several limitations to address with respect to this study. As previously mentioned, internal loading values are affected by multiple factors including running speed, footwear, and foot strike pattern. The participants in this study ran at a self-selected easy running pace, indicating relatively normal loads being experienced during the majority of their running. All participants also wore their typical running shoes, with no participants using minimalist or ultra-cushioning shoes. Thus, these results may be generalized to most runners, but caution should be taken when interpreting in context of different footwear. Regarding foot strike pattern, participants were allowed to use their natural foot strike pattern, and therefore, the sample displayed a combination of rearfoot, midfoot, and forefoot patterns. In addition to these factors, internal loading is contingent on the musculoskeletal model used for analysis. Models such as the one used in the current study are previously established to estimate in vivo forces but are not specific to participants. Therefore, caution may be taken if interpreting absolute loading values alone. However, because this study was focus on relative relations, determining absolute loading of tissues was not a primary objective, and therefore, the current results may still provide meaningful insight.

One consideration is that the present study focused solely on coordination variability rather than accounting for coordination patterns. Injured runners have been shown to display greater amounts of mechanically unsound or antiphase movement, indicating joints or segments rotating in opposing directions from their anatomically linked motion. It was suggested that some combination of amount of variability and time spent in mechanically unsound patterns leads to running-related overuse injuries. Therefore, future studies may investigate whether coordination patterns are also associated with internal loading. This study was also limited by its
use of healthy, recreational runners, and therefore results cannot be directly applied to injured populations. However, the results may still give valuable insight for potential prospective studies for injury development.

Conclusion

There was a relationship between coordination variability and peak loading in the patellofemoral joint and Achilles tendon, where decreased variability predicted greater tissue loading. This does not support the theory that reduced variability leads to increased cumulative loading. Instead, it suggests that coordination variability may play a role in RROIs by increasing the frequency that specific tissues undergo peak loads. Future studies may seek to determine whether individuals with a combination of low variability and large peak loading develop RROIs.
Table 1. Mean (± standard deviation) variability metrics (knee-shank, knee-rearfoot, shank-rearfoot), Achilles tendon (AT) metrics (peak plantarflexor moment, peak AT force, peak loading rate, impulse, cumulative impulse), and patellofemoral (PF) metrics (peak knee extensor (KE) moment, peak PF contact force, peak PF joint stress, peak loading rate, impulse, cumulative impulse).

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<td>Impulse per km (BW*s/km)</td>
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</tbody>
</table>
Table 2. Factor loading scores for Achilles tendon (AT) and patellofemoral (PF, KE = knee extensor) metrics. *denotes factor PF metrics were loaded onto

<table>
<thead>
<tr>
<th>AT Metric</th>
<th>Factor 1</th>
<th>PF Metric</th>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT Force</td>
<td>0.969</td>
<td>KE Moment</td>
<td>0.940*</td>
<td>0.151</td>
</tr>
<tr>
<td>Plantarflex Moment</td>
<td>0.966</td>
<td>PF Contact Force</td>
<td>0.919*</td>
<td>0.266</td>
</tr>
<tr>
<td>AT Impulse</td>
<td>0.942</td>
<td>PF Loading Rate</td>
<td>0.871*</td>
<td>0.052</td>
</tr>
<tr>
<td>AT Loading Rate</td>
<td>0.937</td>
<td>PF Joint Stress</td>
<td>0.800*</td>
<td>0.539</td>
</tr>
<tr>
<td>AT Cumulative Impulse</td>
<td>0.773</td>
<td>PF Cumulative Impulse</td>
<td>0.017</td>
<td>0.981*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PF Impulse</td>
<td>0.425</td>
<td>0.891*</td>
</tr>
</tbody>
</table>
Figure 1. Achilles tendon loading surrogate values with respect to mean knee-rearfoot variability across stance (°). Surrogate values were calculated as the average of Achilles tendon metrics loaded onto Achilles tendon Factor 1 (Table 2) and are unitless.
Figure 2. Patellofemoral peak loading surrogate values with respect to mean (a) knee-rearfoot variability (°) and (b) knee-shank variability (°) across stance. Surrogate values were calculated as the average of patellofemoral metrics loaded onto patellofemoral Factor 1 (Table 2) and are unitless.
References


CHAPTER FOUR

COMPARISON OF COORDINATION AND COORDINATION VARIABILITY BETWEEN ADOLESCENT AND ADULT RUNNERS

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

Author: Allison Hoffee
Contributions: development of research question, performing data collection, data processing and analysis, statistical analysis, writing, revisions and editing of manuscript

Co-Author: Scott Monfort
Contributions: development of research question, revisions and editing of manuscript

Co-Author: David Graham
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Abstract

Running-related injuries are common in both adolescents and adults, but these age groups experience different frequencies of injuries. Coordination variability may give greater insight into the mechanisms behind these injuries in runners of different ages. The purpose of this study was to evaluate differences in coordination and coordination variability between adolescent and collegiate runners. Thigh, shank, and rearfoot segment kinematics were recorded using 3D motion capture for 21 adolescent and 21 collegiate runners. Coordination and coordination variability (CAV) were calculated for four segment couplings using a modified vector coding technique for four couplings: thigh-shank sagittal, thigh-shank transverse, thigh sagittal-shank transverse, and shank transverse-rearfoot frontal. Coordination patterns were classified as in-phase or antiphase motion using a binning frequency analysis, and segment orientation range of motion was calculated. Differences between adolescent and collegiate runners were determined using Mann-Whitney U tests for binning frequencies and segment ranges of motion, circular ANOVAs for mean coupling angles, and factorial ANOVAs for CAV over early, mid, and late stance. Coordination patterns were not different between groups for the thigh-shank sagittal plane (T-S-sag) coupling (p > 0.05). Collegiate runners displayed more in-phase motion than adolescents for the thigh-shank transverse (T-S-trans) coupling (p ≤ 0.008). Adolescent runners displayed more in-phase motion than collegiate runners for the thigh sagittal-shank transverse (Tsag-Strans, p ≤ 0.029) and shank-rearfoot (S-RF, p ≤ 0.011) couplings. Adolescents had greater CAV than collegiate runners for T-S-sag (p = 0.008), T-S-trans (p = 0.011), and S-RF couplings (p = 0.001). The differences in coordination patterns and greater variability seen in adolescents may help to resolve differences in injury risk between youth and adult runners.
Introduction

Running is a popular form of physical activity across the life span, with large participation numbers among both adult\textsuperscript{1} and youth athletes.\textsuperscript{2,3} There is a broad range of reasons individuals run, varying from a competitive activity to general recreation and wellness.\textsuperscript{4} Despite the popularity of running, the rate of injuries associated with running remains high, with up to 79\% of runners experience an injury within any one-year period,\textsuperscript{5} and over 50\% of runners report experiencing multiple injuries.\textsuperscript{1,4} Unfortunately, injury does not discriminate with regard to age as youth runner also experience injuries at high rates, with at least 46\% of youth runners experiencing and injury each year.\textsuperscript{2,6–8} While older and younger runners both experience high rates of injury, the frequencies of specific injuries differ between age groups. For example, older adult runners tend to experience Achilles tendinopathy more than younger adults,\textsuperscript{1,9} whereas high school runners have higher incidences of tibial stress injuries.\textsuperscript{6} These differences drive the question as to whether risk factors for injury development differ in these age groups.

One way to evaluate potential risk of injury is to assess how movement is coordinated across multiple joints in the lower extremity as well as the variability of these coordination patterns across movement cycles. Assessment of coordination patterns can reveal the extent to which a runner uses mechanically sound movements,\textsuperscript{10} while assessment of coordination variability quantifies the different ways in which the system may reach an end goal and the flexibility of that system to adapt to perturbations between movement cycles.\textsuperscript{11} Vector coding is one method which can be used to quantify coordination, and the variability in coordination, of the relative motion between two segments.\textsuperscript{12–14} Vector coding has been used to identify differences in coordination and coordination variability between healthy runners and those
currently injured with patellofemoral pain syndrome\textsuperscript{15,16} or lower back pain,\textsuperscript{17} and recently has been shown to differentiate between runners who remain healthy and those who prospectively develop a running related injury.\textsuperscript{10}

Altered coordination and coordination variability may also occur with aging.\textsuperscript{18,19} Compared to young adults, older adults display reduced coordination variability during both walking and running.\textsuperscript{19,20} This decrease in coordination variability is considered detrimental to healthy aging as it has been previously associated with increased risk of falls in older populations.\textsuperscript{21,22} However, Freedman Silvernail et al.\textsuperscript{23} found that older adults who are active runners have similar variability to their young adult counterparts while Hafer and Boyer\textsuperscript{19} showed that active older adults have greater coordination variability than sedentary older adults. Combined, these results suggest continued physical activity throughout the lifespan can positively impact coordination and coordination variability.

While there is a growing body of literature evaluating coordination and its variability in older adults, relatively little is known regarding these measures at the opposite end the aging spectrum in adolescents. It is possible that the downward decline in coordination variability observed with age continues in reverse through adolescence, with younger individuals displaying greater coordination variability. For example, gross motor development continues through adolescence, where proficiency in fundamental movement skills such as running and jumping stabilizes.\textsuperscript{24} Because of this, adolescent runners may have not yet developed a mastery of the redundant degrees of freedom and may, therefore, display greater coordination variability during running. Alternatively, due to their age, adolescents inherently have less running experience than older runners. Less experienced adult runners display less coordination variability during
running, and therefore this difference may be similar in adolescents with their inherent inexperience.

To date, no studies have evaluated coordination variability in youth runners. Given this gap in the literature, combined with the potential benefits of coordination variability for evaluating running injury risk, popularity of running among youth athletes, and high incidence of injury among adolescent runners, the purpose of this study was to both characterize coordination and coordination variability during treadmill running in adolescent runners and compare these measures between adolescent and young adult runners.

Methods

Participants

Twenty-one adolescent (12 M/9 F, age: 12.38 ± 0.80 years, height: 1.58 ± 0.09 m, mass: 41.61 ± 6.95 kg) and twenty-one collegiate (9 M/12 F, age: 19.76 ± 1.23 years, height: 1.72 ± 0.09 m, mass: 57.1 ± 8.43 kg) runners participated in this study. Participants were recruited from a local youth track club between August and September 2019 and collegiate track team between August and October 2018, respectively. For all participants, inclusion criteria included currently running in competitive competitions, running for at least 15 miles per week, no history of lower extremity surgery, and no lower extremity injuries in the three months prior to testing. All protocols in this study were approved by the Institutional Review Board and both participants and legal guardians for adolescent participants, provided written informed consent prior to participating.
Protocol

Participants completed a five-minute warmup at self-selected pace followed by a five-minute run at their easy training run pace (adolescent: 3.25 ± 0.17 m/s; collegiate: 3.64 ± 0.26 m/s). Whole body kinematics were collected during the last minute of the run using a 6-camera motion capture system (Motion Analysis, Rohnert Park, CA) sampling at 250 Hz. All running was performed on an instrumented treadmill (Treadmetrix, Park City, UT) sampling at 1000 Hz. To define anatomic coordinate systems, retro-reflective markers were placed bilaterally on the anterior and posterior superior iliac spines, medial and lateral femoral condyles, medial and lateral malleoli, and head of second metatarsal. Additional tracking markers were placed bilaterally on the iliac crests, tibial tuberosity, base of the fifth metatarsal, and three on the heel counter of the shoe. Heel counter markers were carefully placed so two were aligned vertically with one on the lateral side. Lastly, rigid clusters with four markers were placed on the lateral thigh and shank and secured with elastic wrap.

Data Reduction and Analysis

Raw marker trajectories and ground reaction forces were exported to Visual 3D (C-Motion, Inc., Germantown, MD, USA) where they were filtered using 4th order, lowpass Butterworth filters with cutoff frequencies of 8 and 50 Hz, respectively. Foot strike and toe off events were identified using a threshold of 50 N in the vertical ground reaction force. In order to obtain reliable coordination variability metrics, twenty consecutive gait cycles were extracted for analysis. Segment orientations for the thigh, shank, and rearfoot were calculated with respect to the lab coordinate system using a YXZ Cardan rotation sequence corresponding to flexion/extension, abduction/adduction, and axial rotation. Segment orientations were
normalized to 100% of stance phase, and segment ranges of motion (ROM) were calculated for the thigh and shank in the sagittal plane and transverse plane, as well as for the rearfoot in the frontal plane.

Coordination patterns and coordination variability were calculated using a modified vector coding technique and custom MATLAB code (MathWorks, Natick, MA). Relative motion plots between two segments were created with the proximal segment on the x-axis and distal segment on the y-axis. A coupling angle (CA) was defined as the orientation of the vector between two consecutive time points relative to the right horizontal axis, and CA were bound from 0 to 360°. Mean CAs at each time point were calculated using circular statistics. CAs were calculated for the following segment couplings: thigh sagittal rotation-shank sagittal rotation (T-S-sag), thigh transverse rotation-shank transverse rotation (T-S-trans), thigh sagittal rotation-shank transverse rotation (Tsag-Strans), and shank transverse rotation-rearfoot frontal rotation (S-RF). These couplings were specifically chosen as they are often assessed in healthy runners and those with common running injuries such as patellofemoral pain syndrome.

A binning frequency analysis was used to classify CAs as either in-phase or antiphase. In-phase patterns involved both segments rotating in the same direction (i.e., both anteriorly rotating or both internally rotating) while antiphase patterns involved segments rotating in opposite directions (i.e. one positive and the other negative or vice versa). Patterns were also classified as displaying proximal dominancy, where the proximal segment moves more than the distal segment, or distal dominancy, where the distal segment moves more than the proximal segment. Combined, this resulted in eight different coordination patterns: in-phase with proximal dominancy (IPPD++ and IPPD--), in-phase with distal dominancy (IPDD++ and IPDD--),
antiphase with proximal dominancy (APPD+- and APPD-+), and antiphase with distal
dominancy (APDD+- and APDD-+). These patterns move in accordance with anatomically
linked movement and may help to resolve motion that leads to increased tissue loading. CA
values corresponding to each coordination pattern for each segment are shown in Table 1.
Variability in coupling angles (CAV) was then calculated as the circular standard deviation of
the CA at each time point of stance phase. For each of the four coupling angles analyzed, the
circular mean of CA, linear mean of CAV, and frequencies with which each of the eight coupling
patterns occurred were calculated for early stance (ES; 0-33%), mid stance (MS; 34-66%), and
late stance (LS; 67-100%).

Statistical Analysis

Due to non-normal distribution of segment ROMs, non-parametric Mann-Whitney U
tests were used to determine differences in segment orientations between adolescent and
collegiate runners. Circular ANOVAs were used to determine differences in mean CA during
each phase of stance between adolescent and collegiate runners. Circular ANOVAs were used to
determine differences in mean CA during each phase of stance between adolescent and collegiate runners. Two x three (group x phase of stance) ANOVAs were used to analyze differences in CAV between adolescent and collegiate groups. In the event of significant
omnibus tests, post hoc comparisons with a Bonferroni correction were completed and effect
sizes (Cohen’s d) were computed. All alpha levels were set to 0.05. All statistics were performed
using Statistical Package for the Social Sciences (SPSS, IBM Corp, Armonk, NY).
Results

Segment Orientations

Mean thigh, shank, and rearfoot segment orientations over stance phase are shown in Figure 1. Thigh sagittal (p < 0.001, d = 1.78), shank sagittal (p = 0.004, d = 0.96), and rearfoot frontal ROM (p = 0.043, d = 0.60) were greater in the collegiate runners than the adolescent runners. Shank transverse ROM was greater in the adolescent runners than the collegiate runners (p < 0.001, d = 1.32). Thigh transverse ROM was not different between groups (p = 0.274, d = 0.36).

Mean Coupling Angles and Bin Frequency

Mean coupling angles over stance phase are shown in Figure 2 while the bin frequencies are shown in Figure 3. For T-S-sag, mean CAs between groups for any phases of stance (ES: p = 0.087, MS: p = 0.705; LS: p = 0.289), and bin frequencies were not different during any phase (all p > 0.05). For T-S-trans, mean CAs were different during all three phases of stance (ES: p < 0.001, MS: p = 0.04; LS: p < 0.001). During ES, adolescent runners spent more time in IPPD++ (p = 0.015, d = 1.15), IPDD++ (p < 0.001, d = 2.26), and APDD-+ (p = 0.001, d = 1.24) than collegiate runners and less time in IPPD-- (p < 0.001, d = 2.17), IPDD-- (p = 0.033, d = 0.90), and APPD+- (p = 0.001, d = 1.21) patterns. During MS, adolescent runners spent more time in APPD+- (p = 0.026, d = 0.67) and less time in APDD-+ (p = 0.022, d = 0.63) than collegiate runners. During LS, adolescent runners spent more time in APDD+- (p = 0.001, d = 1.37) and APPD+- (p = 0.005, d = 1.25) than collegiate runners and less time in IPPD++ (p = 0.008, d = 1.12), IPPP-- (p = 0.003, d = 1.48), IPDD++ (p = 0.007, d = 1.03), and APPD-+ (p = 0.007, d = 0.92).
For Tsag-Strans, mean CAs were different for ES (p < 0.001) and LS (p = 0.025). During ES, adolescent runners spent more time in IPDD++ (p < 0.001, d = 1.54) and APDD-+ (p < 0.001, d = 1.38) than collegiate runners, but less time in APDD+- (p = 0.011, d = 0.69), APPD+- (p = 0.033, d = 0.89), APPD-+ (p = 0.016, d = 0.94), IPPD-- (p < 0.001, d = 1.36), and IPDD-- (p < 0.001, d = 1.45). During LS, adolescent runners spent more time in IPPD-- (p < 0.001, d = 1.87) and less time in APPD-+ (p < 0.001, d = 1.87) than collegiate runners. While mean CAs were not different between groups during MS (p = 0.36), adolescent runners spent more time in IPPD-- (p = 0.029, d = 0.77) and less time in APPD-+ (p = 0.018, d = 0.82) than collegiate runners.

For S-RF, mean CAs were different for the collegiate group than the adolescent group for all three phases of stance (ES: p < 0.001, MS: p = 0.011, LS: p < 0.001). During ES, adolescent runners spent more time in IPPD++ (p = 0.001, d = 1.18) and IPDD++ (p = 0.002, d = 1.12) than collegiate runners and less time in APDD-+ (p < 0.001, d = 2.26). During MS, adolescent runners spent more time in IPPD++ (p = 0.001, d = 1.18) and IPDD-- (p = 0.006, d = 0.86) and less time in APDD+- (p = 0.002, d = 1.10) than collegiate runners. Finally, during LS adolescent runners spent more time in IPDD-- (p = 0.011, d = 0.91) and less time in APDD+- (p < 0.001, d = 1.86) than collegiate runners.

**Coupling Angle Variability (CAV)**

Mean CAV for all four couplings are shown in Figure 4. For T-S-sag, there was a group-by-phase interaction (p = 0.008). Specifically, CAV was greater in the adolescent than collegiate runners during ES (p < 0.001, d = 2.30), MS (p < 0.001, d = 1.54), and LS (p = 0.001, d = 1.10). However, within the adolescents, CAV was smaller during LS than both ES (p < 0.001, d = 1.54) and
MS (p < 0.001, d = 0.95) whereas CAV did not differ between any phases of stance for the collegiate group (all p > 0.05).

For T-S-trans, there was no significant interaction (p = 0.78), but there were main effects of group (p = 0.011) and phase of stance (p = 0.003). Adolescents had overall higher CAV than collegiate runners (p = 0.011, d = 0.64) and CAV during LS was larger than during ES, regardless of group (p = 0.001, d = 0.61). For Tsag-Strans, there was not a significant interaction (p = 0.25) or main effect of group (p = 0.622), but there was a main effect of phase of stance (p < 0.001). CAV during ES was larger than both MS (p < 0.001, d = 2.76) and LS (p < 0.001, d = 2.85), regardless of group.

For S-RF, there was no significant interaction (p = 0.28) but there were main effects of group (p = 0.001) and phase of stance (p < 0.001). CAV for the adolescent group was overall higher than for the collegiate group (p = 0.001, d = 0.81) and CAV was higher during MS than both ES (p < 0.001, d = 1.17) and LS (p < 0.001, d = 0.69), regardless of group.

Discussion

The purpose of this study was to evaluate differences in coordination and coordination variability between adolescent and collegiate runners. Differences were seen in overall segment orientations, coordination patterns, and coordination variability between adolescents and collegiate runners. Adolescent runners displayed less segment ranges of motion in the sagittal and frontal planes than collegiate runners, whereas collegiate runners displayed less transverse rotation of the shank. These differences may indicate that age may play a role in the running mechanics seen in these groups of runners, which may translate to some differences seen in
coordination patterns. This may be most relevant to couplings involving transverse shank motion due to this being the only motion that was smaller in collegiate runners.

Adolescent runners had overall different coordination patterns than collegiate runners with the exception for relative sagittal plane motion. T-S-sag coupling angles and patterns were similar between adolescent and collegiate runners. This coupling describes how the knee flexion is coordinated through stance phase, and therefore, these similarities between age groups indicate that the way in which adolescent and collegiate runners coordinate knee flexion during stance phase is similar. No other segment couplings were similar. For the T-S-trans coupling, adolescent and collegiate runners spent similar amounts of time moving in an in-phase pattern during ES but differed in the direction of motion. During LS, collegiate runners utilized more in-phase motion while adolescents utilized more antiphase motion. Previous studies have suggested that antiphase motion may lead to increased loading of soft tissue structures in the knee, which has been noted as a risk of injury.\textsuperscript{10,32} This may suggest that adolescents’ coordination patterns during late stance in the transverse plane may be placing them at a slightly greater risk of injury.

Both adolescent and collegiate runners used a wide variety of coordination patterns during ES for the Tsag-Strans coupling. This may be due to the nature of how the knee absorbs loads during running. Because of the anatomy of the knee, internal rotation of the shank naturally occurs with flexion of the knee joint. While these motions are anatomically linked, knee flexion may occur with both anterior and posterior rotation of the thigh. Therefore, sagittal thigh rotation and transverse shank rotation may not be specifically linked, indicating that it may not be problematic for antiphase motion to occur during ES for this coupling. MS and LS were both dominated by two coordination patterns, with collegiate runners spending more time antiphase
than adolescent runners, which was unexpected. It would be expected for the thigh to continue rotating posteriorly through stance while the shank switches from internal to external rotation. This suggests that the collegiate runners’ increased antiphase patterns during LS may be unfavorable in terms of injury. S-RF coupling angles and patterns differed between age groups during all phases of stance. In-phase motion of the S-RF coupling indicates anatomically linked motion, where the shank internally rotates with rearfoot eversion and externally rotates with rearfoot inversion. Throughout all of stance, the adolescent runners spent more time in these in-phase patterns while the collegiate runners spent more time in antiphase motion. Again, this was the amount of time spent in antiphase motion for the collegiate groups was unexpected. Antiphase motion in the S-RF coupling may result in greater stress at the knee joint due to the anatomically linked movement, and may potentially increase the likelihood of injury in the collegiate runners.

Previous literature has suggested decreasing coordination variability with aging, where older adults have less variability than younger adults. The results of the present study support this behavior. This has specifically been shown during midstance for Tsag-Strans and SRF, with T-S-sag also during terminal swing. While these results are not explicitly similar to the results of the present study, they do follow a similar trend, where older individuals display less variability than younger individuals. The differences in adolescent and adult variability are supported by the ongoing motor development of adolescents, where coordination variability may be viewed as an assessment of the mastery of redundant degrees of freedom of a system. Therefore, the large amount of variability seen in adolescent runners may be interpreted as a lack of mastery of the movement, where they are continuing to improve movement proficiency.
Coordination variability is often greater at the inflection point within a movement, or in other words, as a segment transitions from rotation in the positive direction to rotation in the negative direction.\textsuperscript{15,35} This is partially due to the inherent nature of vector coding, where the CA may have vastly different orientations due to the timing of that transition to a new coordination pattern. This is seen in the S-RF coupling, where both adolescent and collegiate groups display greater variability during MS and different coordination patterns during ES and LS. Coordination variability is also described as the flexibility within a system to respond to perturbations,\textsuperscript{11} which explains the large amount of variability during ES for Tsag-Strans. This variability allows for the knee joint to be loaded in a slightly different way during each gait cycle, which may decrease potential for injury.\textsuperscript{29} Variability in the T-S-sag coupling is the only place where differences between phases of stance were seen in the adolescent group but not the collegiate group. Specifically, adolescents showed less variability during LS than either ES or MS whereas the collegiate group had similar amounts of variability through all phases of stance. This may indicate a lack of flexibility in knee flexion in the adolescent group and that adolescent runners may have a more consistent position of knee flexion during toe-off than collegiate runners.

There are a few limitations to this study. Collegiate runners were being classified as adult runners. However, in terms of development and movement proficiency, this may not be accurate. Previous studies suggest that individuals are still developing some amount of proficiency through late adolescence and young adulthood.\textsuperscript{24} Because of the proximity to adolescents of the collegiate runners, it is possible they were not representative of coordination variability seen in more mature adults. However, movement proficiency is greater in adults who were also active as children,\textsuperscript{38} suggesting that their coordination patterns and proficiency may stable. Because our
collegiate population consisted of student athletes who had been active for years, it may be assumed that their proficiency in running, and therefore their coordination, are at a consistent level. The present study also included experienced, competitive runners for both adolescent and collegiate groups. Previous literature suggests that experience plays a role in coordination, where novice runners display less coordination variability than experienced runners.26 Future studies may seek to resolve the trends in coordination in adolescent runners who are not competitive to determine whether experience also plays a role before adulthood.

Other considerations of this study include sex and speed. It is unclear how coordination patterns and variability differ with sex, as some studies have shown differences male and female runners18,39 and other studies have found no effect of sex on coordination variability.40 Similarly, discrepancies in literature exist on the effect of running speed on coordination variability. For example, assessments of running speed have shown no effects on variability,41 whereas an increase in running cadence has been associated with both an increase42 and a decrease43 in variability. The inconsistencies in literature suggest that neither of these variables may be as important to the changes seen in the current results between adolescent and adult runners as the age of our populations. Nevertheless, these discrepancies warrant further investigation into the effects of sex and running speed on coordination patterns and variability.

In conclusion, adolescent runners display different intersegmental coordination patterns than collegiate runners. Adolescent runners also displayed greater coordination variability through stance phase, supporting a general reduction in variability through the life span. As coordination and variability are often assessed in terms of injury, resolving these differences in coordination may bring insight into differences in injury between age groups.
Table 1. Coordination pattern classifications for binning frequency analysis. Coordination patterns are based on the coupling angle magnitude as described by Needham (2015). Directionality of segment orientations are based on anatomically linked motion, where positive rotations are defined as the motion of the distal end of the segment relative to the proximal end.

<table>
<thead>
<tr>
<th>Pattern Denotation</th>
<th>Direction (Prox/Dist)</th>
<th>Coordination Pattern</th>
<th>Coupling Angle Magnitude (°)</th>
<th>Thigh-Shank Sag</th>
<th>Thigh-Shank Trans</th>
<th>Thigh Sag-Shank Trans</th>
<th>Shank-Rearfoot</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPPD++</td>
<td>+/+</td>
<td>In-phase, proximal dominancy</td>
<td>0 &lt; CA &lt; 45</td>
<td>Ant/Ant</td>
<td>IR/IR</td>
<td>Ant/IR</td>
<td>IR/Lat</td>
</tr>
<tr>
<td>IPPD--</td>
<td>+/-</td>
<td></td>
<td>180 &lt; CA &lt; 225</td>
<td>Post/Post</td>
<td>ER/ER</td>
<td>Post/ER</td>
<td>ER/Med</td>
</tr>
<tr>
<td>IPDD++</td>
<td>+/-</td>
<td>In-phase, distal dominancy</td>
<td>45 &lt; CA &lt; 90</td>
<td>Ant/Ant</td>
<td>IR/IR</td>
<td>Ant/IR</td>
<td>IR/Lat</td>
</tr>
<tr>
<td>IPDD--</td>
<td>-/-</td>
<td></td>
<td>225 &lt; CA &lt; 270</td>
<td>Post/Post</td>
<td>ER/ER</td>
<td>Post/ER</td>
<td>ER/Med</td>
</tr>
<tr>
<td>APDD+</td>
<td>+/-</td>
<td>Antiphase, distal dominancy</td>
<td>90 &lt; CA &lt; 135</td>
<td>Post/Ant</td>
<td>ER/IR</td>
<td>Post/IR</td>
<td>ER/Lat</td>
</tr>
<tr>
<td>APDD-</td>
<td>+/-</td>
<td></td>
<td>270 &lt; CA &lt; 315</td>
<td>Ant/Post</td>
<td>IR/ER</td>
<td>Ant/ER</td>
<td>IR/Med</td>
</tr>
<tr>
<td>APD+</td>
<td>+/+</td>
<td>Antiphase, proximal dominancy</td>
<td>135 &lt; CA &lt; 180</td>
<td>Post/Ant</td>
<td>ER/IR</td>
<td>Post/IR</td>
<td>ER/Lat</td>
</tr>
<tr>
<td>APD-</td>
<td>+/-</td>
<td></td>
<td>315 &lt; CA &lt; 360</td>
<td>Ant/Post</td>
<td>IR/ER</td>
<td>Ant/ER</td>
<td>IR/Med</td>
</tr>
</tbody>
</table>
Figure 1. Segment orientations (°) over time for thigh sagittal plane, shank sagittal plane, thigh transverse plane, shank transverse plane, and rearfoot frontal plane for adolescent (green) and collegiate (black) groups.
Figure 2. Mean coupling angle for thigh-shank sagittal, thigh-shank transverse, thigh sagittal-shank transverse, and shank transverse-rearfoot eversion coupling angle variability of adolescent (green) and collegiate (black) groups during phases of stance. *differences between adolescent and collegiate groups (p < 0.05)
Figure 3. Mean binning frequencies of all segment couplings for adolescent (green) and collegiate (black) groups over phases of stance, expressed as percent of total phase. (IPPD = in-phase with proximal dominancy; IPDD = in-phase with distal dominancy; APDD = antiphase with distal dominancy; APPD = antiphase with proximal dominancy) *differences between adolescent and collegiate groups (p < 0.05)
Figure 4. Mean variability for thigh-shank sagittal, thigh-shank transverse, thigh sagittal-shank transverse, and shank transverse-rearfoot frontal segment couplings of adolescent (green) and collegiate (black) runners. *indicates main effects of group between AR and CR a, b, and c indicate differences between phases of stance: aES and MS, bMS and LS, and cES and LS. #significantly different from late stance within AR (p < 0.05)
References


25. Mo S, Chow DHK. Differences in lower-limb coordination and coordination variability between novice and experienced runners during a prolonged treadmill run at anaerobic


38. Stodden D, Langendorfer S, Roberton MA. The association between motor skill


CHAPTER FIVE

DISCUSSION AND CONCLUSIONS

The aim of this thesis was to expand on current knowledge of coordination and coordination variability during running with respect to internal loading and age. Coordination and its variability have been linked to various running injuries\(^1\)\(^-\)\(^3\) such as patellofemoral pain syndrome.\(^4\)\(^,\)\(^5\) However, it is unclear whether altered coordination is a driving factor or a product of those injuries, as injured runners have exhibited both increased\(^2\)\(^,\)\(^3\)\(^,\)\(^5\) and decreased\(^3\)\(^,\)\(^4\) variability compared to healthy runners. One theory proposed suggests that reduced coordination variability may be a driving factor of injury.\(^1\) Specifically, individuals with reduced variability will naturally load soft tissue structures in a similar way on every step, thus increasing the cumulative load and surpassing the injury threshold of that tissue.\(^1\)\(^,\)\(^6\) It is important to quantitatively assess this relationship as it may lead to different consequences in different age populations. This is evident due to differences seen in concerns such as injury, where injuries like Achilles tendinopathy are more prevalent in older adult runners\(^7\) and tibial stress injuries are more prevalent in adolescent runners.\(^8\) Similarly, older adults tend to display different coordination patterns and coordination variability than younger adults, which may potentially play a role in these concerns.\(^9\)\(^,\)\(^10\) Despite this research assessing coordination and variability through adulthood, little is known about coordination during running during adolescence.

The purpose of Study 1 was to build upon the theoretic relationship between coordination variability and internal loading, specifically to establish whether runners with less coordination variability would also display greater internal loading. Loading was assessed for the Achilles tendon (AT) and patellofemoral (PF) joint. The results of Study 1 indicated a relationship
between coordination variability and the surrogate variable “Achilles loading,” where greater
knee-rearfoot variability was associated with lower “Achilles loading.” The surrogate variable
was an average of peak plantar flexor moment, peak AT force, peak AT loading rate, impulse,
and impulse per kilometer. These results indicate that a combination of motion both at the
rearfoot and the knee joint may be important for how the AT is loaded during running. In terms
of PF loading, there was a relationship between coordination variability and the surrogate
variable “peak PF loads.” Both knee-shank and knee-rearfoot variability predicted “peak PF
loads,” where greater amounts of variability in both coupling metrics were associated with lower
“peak PF loads.” This surrogate variable consisted of peak knee extensor moments, peak PF joint
contact force, peak PF joint stress, and peak PF loading rate. No coordination variability metrics
significantly predicted the surrogate variable “cumulative PF loads,” which consisted of PF
impulse and PF impulse per kilometer. Together, these results may suggest that peak amounts of
loading applied to the PF joint may potentially be more important to running in terms of linking
variability to injury than how that load is applied over time. Overall, the results of Study 1
propose a link between coordination variability and internal loading, which may give some
insight into potential factors such as mechanisms of injury.

The purpose of Study 2 was to evaluate the differences in coordination and coordination
variability between competitive adolescent and collegiate runners. Segment couplings between
the thigh, shank, and rearfoot segments was assessed to understand how knee and ankle
kinematics are coordinated during running. Overall, adolescent runners displayed different
coordination patterns for thigh-shank transverse, thigh sagittal-shank transverse, and shank
transverse-rearfoot frontal couplings. Specifically, adolescents displayed more anti-phase motion
in the thigh-shank transverse coupling during late stance than collegiates. Additionally, adolescent runners overall displayed more in-phase motion for the thigh sagittal-shank transverse and shank transverse-rearfoot frontal couplings, which was not as expected. This may be due to the sample populations and potentially due to the fact that collegiate runners were used. These results indicate that adolescent and collegiate runners coordinate their joint motion during running in different ways. Adolescents did display overall greater coordination variability in for the thigh-shank sagittal, thigh-shank transverse, and shank-rearfoot couplings than collegiate runners. Taken together with previous literature, this suggests that there is a general downward trend in coordination variability starting in adolescence that progressively decreases through adulthood into older adulthood.

Altogether, the results of the present studies supplement the growing body of literature on coordination and coordination variability during running. The results of Study 1 propose a potential mechanism of injury that complements the original theory\(^1\) where runners with reduced coordination variability did also exhibit greater internal loading. In Study 2, adolescents were found to have different coordination patterns and variability while running than collegiate runners. Therefore, the results from Study 1 may be utilized to inform potential consequences of Study 2. Particularly, coordination variability as a potential driving factor of injury development may not be as consequential in adolescent runners as adult runners. Additionally, in light of the differences in injury prevalence for different age populations,\(^7,8\) future research may look to determine whether the relationship between coordination variability and internal loading found in Study 1 differs in different age populations. This may aid in the elucidation of different mechanisms of injuries for these unique populations. As further consideration, while Study 1 was
comprised of healthy participants, the relationship in question between variability and loading arose as a question of injury factors. Therefore, future research may seek to resolve whether those individuals with reduced variability and greater loading go on to develop injuries in the respective tissue structures.

There are several limitations to consider when interpreting the results of these studies. First, internal loading during running has been shown to change with variables such as foot strike pattern, shoe type, and running speed. Because of the exploratory nature of this study, participants were allowed to utilize their natural foot strike pattern and running speed as well as normal footwear. This allowed for variability and loading metrics to be as close as possible to normal running conditions for each participant, which was the desired aim for Study 1. With respect to internal loading metrics, calculation-based musculoskeletal models were used to estimate muscle forces and tissue loading. While these models have been established in previous literature and are considered reliable calculation methods, they are based on generic cadaver studies and therefore are not specific to each participant. This lack of specificity may allow for errors and estimates that are not precise to in vivo loading of tissue structures.

Regarding coordination, both patterns and variability have been linked to injury during running. However, the focus of Study 1 was on coordination variability. Coordination patterns, however, may be equally important as variability in terms of internal loading and injury. In light of the differences in coordination patterns between adolescent and adult runners seen in Study 2, it may be beneficial to determine whether some combination of maladaptive coordination patterns and reduced variability is predictive of internal loading, and how these relationships may change across the lifespan.
In conclusion, individuals with reduced coordination variability also exhibit greater Achilles tendon and peak patellofemoral loading during running. Differences in coordination and coordination variability were also shown between adolescent and collegiate runners, where adolescents displayed greater coordination variability and different patterns of segmental coordination than collegiates during running. Overall, this thesis provided further connections between various factors of running and may provide implications for potential risk of injury in different age populations.
References


CUMULATIVE REFERENCES CITED


14. Farrokhi S, Keyak JH, Powers CM. Individuals with patellofemoral pain exhibit greater


54. Wheat JS, Glazier PS. Measuring Coordination and Variability in Coordination. In:


APPENDIX A

SUPPLEMENTAL DATA FOR CHAPTER THREE
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/FORMAT SORT

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/EXTRACTION PC

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Extraction Method: Principal Component Analysis.

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Extraction Method: Principal Component Analysis.$^a$

$^a$ 2 components extracted.
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Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

* Rotation converged in 3 iterations.

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Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

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Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Component Scores.

**Component Score Covariance Matrix**

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Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Component Scores.

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AT Cum Imp & .774 & \\
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Extraction Method: Principal Component Analysis.\textsuperscript{a}

\textsuperscript{a} 1 components extracted.
Rotated Component Matrix

a. Only one component was extracted. The solution cannot be rotated.

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Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Component Scores.

Component Score Covariance Matrix

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COMPUTE PFcumulative_surrogate=MEAN(PFImp,PFCumImp).
EXECUTE.

COMPUTE
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/NOORIGIN
/DEPENDENT
PFcumulative_surrogate
/METHOD=ENTER
PFpeak_surrogate
/SAVE ZRESID.

Resources

<table>
<thead>
<tr>
<th>Resources</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor Time</td>
<td>00:00:00.03</td>
</tr>
<tr>
<td>Elapsed Time</td>
<td>00:00:00.03</td>
</tr>
<tr>
<td>Memory Required</td>
<td>3008 bytes</td>
</tr>
<tr>
<td>Additional Memory Required for Residual Plots</td>
<td>0 bytes</td>
</tr>
</tbody>
</table>

Variables Created or Modified

<table>
<thead>
<tr>
<th>Variables Created or Modified</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZRE_1</td>
<td>Standardized Residual</td>
</tr>
</tbody>
</table>

Variables Entered/Removed\(^a\)

<table>
<thead>
<tr>
<th>Model</th>
<th>Variables Entered</th>
<th>Variables Removed</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PFpeak_surrogate(^b)</td>
<td></td>
<td>Enter</td>
</tr>
</tbody>
</table>

a. Dependent Variable: PFcumulative_surrogate
b. All requested variables entered.

Model Summary\(^b\)

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.122(^a)</td>
<td>.015</td>
<td>-.001</td>
<td>33.66800</td>
</tr>
</tbody>
</table>
a. Predictors: (Constant), PFpeak_surrogate
b. Dependent Variable: PFcumulative_surrogate

### ANOVA

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>1</td>
<td>1061.361</td>
<td>1061.361</td>
<td>.936</td>
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<tr>
<td></td>
<td>Residual</td>
<td>62</td>
<td>1133.534</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>63</td>
<td>71340.480</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Coefficients

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>117.030</td>
<td>10.047</td>
<td>11.648</td>
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<tr>
<td></td>
<td>PFpeak_surrogate</td>
<td>.229</td>
<td>.237</td>
<td>.122</td>
</tr>
</tbody>
</table>

### Residuals Statistics

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Value</td>
<td>120.6568</td>
<td>138.6810</td>
<td>125.8578</td>
<td>4.10451</td>
<td>64</td>
</tr>
<tr>
<td>Residual</td>
<td>-99.48713</td>
<td>72.96127</td>
<td>.00000</td>
<td>33.39972</td>
<td>64</td>
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<tr>
<td>Std. Predicted Value</td>
<td>-1.267</td>
<td>3.124</td>
<td>.000</td>
<td>.000</td>
<td>64</td>
</tr>
<tr>
<td>Std. Residual</td>
<td>-2.955</td>
<td>2.167</td>
<td>.000</td>
<td>.992</td>
<td>64</td>
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</tbody>
</table>
GRAPH

/SCATTERPLOT(BIVAR)=PFcumulative_factor WITH ZRE_1

/MISSING=LISTWISE.

Graph

<table>
<thead>
<tr>
<th>Output Created</th>
<th>19-FEB-2021 12:24:04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comments</td>
<td></td>
</tr>
<tr>
<td>Input</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td>C:\Users\a-\sta\Documents\Research\Data\Internal Loading and Coordination Variability Running\SurrogateOutput_Data_wo11and50.sav</td>
</tr>
<tr>
<td>Active Dataset</td>
<td>DataSet1</td>
</tr>
<tr>
<td>Filter</td>
<td>&lt;none&gt;</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt;none&gt;</td>
</tr>
<tr>
<td>Split File</td>
<td>&lt;none&gt;</td>
</tr>
<tr>
<td>N of Rows in Working Data File</td>
<td>64</td>
</tr>
</tbody>
</table>
Syntax

```plaintext
GRAPH
/SCATTERPLOT(BIVAR)=PF
  cumulative_factor WITH
  ZRE_1
/MISSING=LISTWISE.
```

<table>
<thead>
<tr>
<th>Resources</th>
<th>Processor Time</th>
<th>00:00:00.44</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Elapsed Time</td>
<td>00:00:00.34</td>
</tr>
</tbody>
</table>

Resources

**Processor Time**: 00:00:00.44
**Elapsed Time**: 00:00:00.34

Graph:

```
GRAPH

/SCATTERPLOT(BIVAR)=ATloading_factor WITH ATloading_surrogate

/MISSING=LISTWISE.
```
## Graph

<table>
<thead>
<tr>
<th>Output Created</th>
<th>19-FEB-2021 12:25:08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comments</td>
<td></td>
</tr>
<tr>
<td>Input Data</td>
<td>C:/Users/a-sta/Documents/Research/Data/Internal Loading and Coordination Variability Running/SurrogateOutput_Data_wo11and50.sav</td>
</tr>
<tr>
<td>Active Dataset</td>
<td>DataSet1</td>
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<tr>
<td>Filter</td>
<td>&lt;none&gt;</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt;none&gt;</td>
</tr>
<tr>
<td>Split File</td>
<td>&lt;none&gt;</td>
</tr>
<tr>
<td>N of Rows in Working Data File</td>
<td>64</td>
</tr>
</tbody>
</table>
| Syntax         | GRAPH
/SCATTERPLOT(BIVAR)=ATloading_factor WITH ATloading_surrogate /MISSING=LISTWISE. |
| Resources      |                      |
| Processor Time | 00:00:00.28          |
| Elapsed Time   | 00:00:00.22          |
DATASET ACTIVATE DataSet1.

SAVE OUTFILE='C:\Users\a-sta\Documents\Research\Data\Internal Loading and Coordination' "+

'Variability Running\SurrogateOutput_Data_wo11and50.sav'

/COMPRESSED.
Regression between Variability and Loading