

Sport Specialization and Coordination Differences in Multisport Adolescent Female Basketball, Soccer, and Volleyball Athletes

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Context: Early sport specialization, or the participation in 1 sport year-round to the exclusion of all others, is a growing concern in youth athletics because of its possible association with musculoskeletal injury. The underlying injury risk may be the result of coordination differences that sport-specialized athletes have been speculated to exhibit relative to multisport athletes; however, little evidence exists to support or refute this notion.

Objective: To examine relative hip- and knee-joint angular-motion variability among adolescent sport-specialized and multisport female adolescent athletes to determine how sport specialization may affect coordination.

Design: Cohort study.

Setting: Research laboratory.

Patients or Other Participants: A total of 366 sport-specialized and 366 multisport adolescent female basketball, soccer, and volleyball players.

Intervention(s): Drop-vertical-jump (DVJ) assessment.

Main Outcome Measure(s): Average coupling-angle variability (CAV) for hip flexion and knee flexion, knee flexion and ankle flexion, hip flexion and knee abduction, knee flexion and

knee abduction, knee flexion and knee internal rotation, and knee abduction and knee internal rotation.

Results: The sport-specialized group exhibited increased coupling variability in dominant-limb hip flexion and knee flexion ($P=.015$), knee flexion and knee abduction ($P=.014$), and knee flexion and knee internal rotation ($P=.048$) while landing during the DVJ, although they had small effect sizes ($\eta^2=0.010$, 0.010 , and 0.007 , respectively). No differences were present between groups for any of the other CAV measures of the dominant limb, and no differences were found for any CAV measures of the nondominant limb (all P values $> .05$).

Conclusions: Sport specialization was associated with increased variability of critical hip- and knee-joint couplings responsible for effective landing during the DVJ. Altered coordination strategies that involve the hip and knee joints may underlie unstable landings, inefficient force-absorption strategies, or greater contact forces that can place the lower extremities at risk for injury (or a combination of these).

Key Words: overuse injuries, youth sports, early specialization, motor skills

Key Points

- Sport-specialized female athletes demonstrated altered lower extremity coordination.
- Altered coordination may lead to less stable landings and an increased injury risk.
- Multisport participation may facilitate improved coordination in youth female athletes.

Currently, the number of youth athletes in the United States who participate in organized sports at either the individual or team level has been estimated to be between 30 and 60 million¹—a steady increase over the last few decades.² Concurrently, increased emphasis has been placed on young athletes' succeeding in sport, often at the behest of their parents, coaches, or even peers.^{3,4} This emphasis has been driven in part by the potential economic benefit of high-level sport achievement, such as collegiate athletic scholarships or attainment of elite or professional status.² As a result of this increased pressure on youth athletes to excel, a growing trend among adolescent athletes is to commit to 1 sport year-round to the exclusion of other sports (ie, *sport specialization*).⁵ Such a commitment is

likely expected to offer athletes an advantage among their sport and peer group(s) and maximize their potential for success. However, growing evidence indicates that sport specialization, and in particular, *early sport specialization* (ie, before or alongside maturation during puberty), may lead to significant health consequences, such as burnout and depression in adolescent athletes,^{1,3} as well as exacerbate the musculoskeletal injury risk.^{6–10} Sport specialization in adolescents was associated with an increased incidence of lower extremity injury in high school athletes⁸ and patellofemoral pain in middle and high school female basketball, soccer, and volleyball athletes.⁷

Why the musculoskeletal injury risk may be increased among sport-specialized adolescent athletes remains un-

clear. Although sport specialization itself is likely not the only risk factor for injury, year-round commitment to a single sport, especially to a sport that involves repetitive motions, such as baseball, gymnastics, or tennis, can lead to overuse and injury in young athletes. For example, adolescent baseball athletes who pitched more than 8 months per calendar year had a nearly 5-fold increased risk for shoulder and elbow injury.¹¹ As a result of athletes' participation in a single sport year-round, the constant or repetitive exposure to stresses could lead to a higher rate of musculoskeletal fatigue and aberrant joint loading and stress that exceed the ability to recover. Another possibility, particularly in the case of the early sport-specialized athlete, is that a year-round commitment to a single sport may affect motor-skill competence during a time of critical foundational skill development. For example, significant evidence suggested that elite athletes, including German Olympic athletes¹² and elite tennis athletes,¹³ specialized later in adolescence. Generalized physical activity facilitates motor development that may be expedited by performing diverse movement patterns that contribute to broad motor competence¹⁴; an excessive focus on singular motor patterns from commitment to a single sport may disrupt the motor-development and motor-coordination processes that are acquired or refined during adolescence.

Coordination in motor task performance is commonly studied in both healthy and pathologic populations. Coordination variability has also been studied extensively, often in pathologic or otherwise compromised populations, such as runners with patellofemoral pain^{15,16} and athletes with anterior cruciate ligament injury.^{17,18} It has generally been established that variability in the movement patterns underlying coordination indicates a healthy motor system,^{15,19–21} which can help an individual adapt to unexpected situations or perturbations, acquire more stable movement patterns, or facilitate new motor learning.^{15,19–21} Rigid, invariable patterns of movement have been postulated to lead to increased injury risk as a result of more continual and nonvarying stresses on musculoskeletal tissue¹⁵; conversely, excessive variability in coordination patterns may accentuate the compromised neuromuscular control that may place the individual at risk for aberrant biomechanical patterns and high-risk joint loads.¹⁷ Therefore, it may be useful to explore potential disruptions in normal coordinative processes in populations already susceptible to injury, such as female adolescent athletes.

A significant rationale exists for identifying possible associations between sport specialization and coordination in young athletes. Therefore, the purpose of our study was to examine coordinative differences among adolescent sport-specialized and multisport female athletes to determine how sport specialization affects motor behavior and coordination. The hypothesis tested was that sport-specialized athletes would exhibit coordinative differences in key joint couplings related to compromised neuromuscular control and aberrant biomechanical loads as compared with multisport athletes.

METHODS

Participants

Data were collected from a total of 1116 adolescent female basketball, soccer, and volleyball athletes who were

enrolled in 1 of 2 studies—a prospective cohort study to detect biomechanical deficits associated with anterior cruciate ligament injury²² or a randomized clinical trial to deliver neuromuscular training to improve these deficits²³—that were administered over 4 years. Both consisted of a 3-dimensional motion-analysis assessment that included a drop-vertical-jump (DVJ) task. Although participants were recruited for 2 different studies, the recruitment processes, target populations, and assessment protocols were identical for both. Participants were recruited mainly from local middle and high schools, but recruitment included local colleges as well. Before data collection, the study protocol was approved by the institutional review board, and informed written consent to participate was obtained from each recruit and, if the recruit was under 18 years of age, her legal guardian.

Participants were recruited and tested before the beginning of their respective competitive sport seasons, and a given testing session represented the athlete's first visit to the laboratory (ie, no athlete had been tested previously). Participants were recruited as part of a team, and all participants from a given team were tested on a single day. Before arriving at the laboratory, participants were instructed to wear their own athletic clothing and footwear so as to facilitate motion assessment. At the beginning of each testing session, participants' anthropometric, demographic, and self-reported measures of maturational status (eg, menses status) and sports participation were recorded. In addition, each athlete's dominant leg was determined by asking which leg she would prefer to use to kick a ball the farthest distance possible.

Inclusion Criteria

Initial inclusion criteria were participants who were healthy female children and adolescents screened relative to predetermined inclusion and exclusion criteria. Volunteers were excluded from the study if they were not enrolled in a school-sponsored basketball, soccer, or volleyball team. Only participants with acceptable-quality 3-dimensional motion data and ≥ 2 years' involvement in at least 1 organized sport (see "Defining Sport Specialization") were included, leaving 938 participants available for further analysis. In the present study, participants were considered to have acceptable-quality motion data if they had ≥ 2 acceptable DVJ trials; a DVJ trial was deemed acceptable if the participant executed the movement correctly and the recorded data were of excellent quality, that is, no major occlusions of markers occurred during the movement. The participants were then match sampled such that age, height, weight, pubertal stage, and sport-specialization status were equally (or close to equally) distributed. The group of 938 was divided into relative subgroups based on pubertal stage and sport specialization, producing 4 subgroups; the smallest of these groups was used to match and sample from the other 3. Specifically, the smallest subgroup—multisport, postpubertal athletes—contained 183 athletes who were subsequently matched with 183 sport-specialized, postpubertal athletes. After this, 366 athletes were sampled from the remaining prepubertal and midpubertal cohort (183 sport-specialized and 183 multisport athletes, respectively), leaving a total of 732 athletes (age = 13.8 \pm

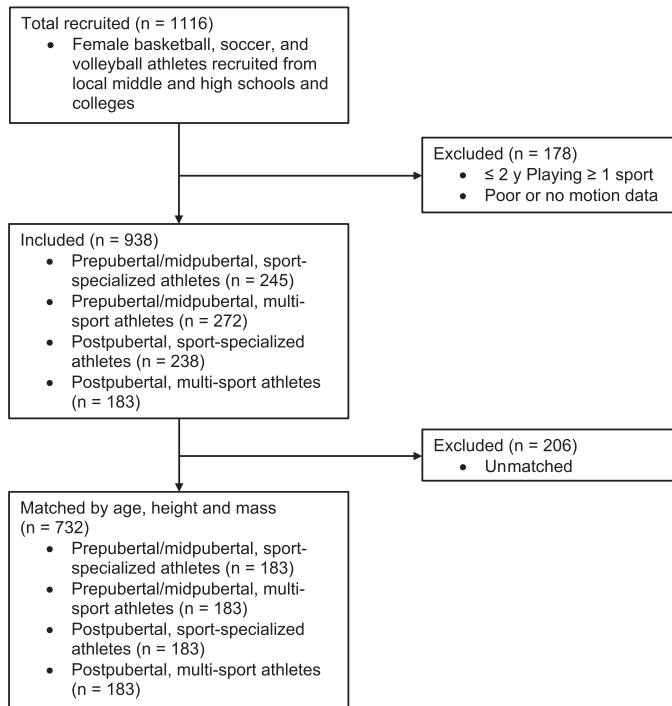


Figure 1. Schematic illustrating the selection process for the cohort of sport-specialized and multisport athletes.

2.0 years, height = 1.61 ± 0.1 m, weight = 55.1 ± 10.3 kg for statistical analysis (Figure 1).

Defining Sport Specialization

Recruits were given a questionnaire that contained 3 survey questions relating to sports participation: “What is your current sport?” “What additional organized sports do you play?” and “What is the number of years you have played the selected sports in the first 2 questions?” For the third question, participants answered in whole years. Athletes were not asked if this was their first year participating in their current sport or when they started participating in any other sports; consequently, the questionnaire did not differentiate between first-time athletes and athletes who had at least 1 year of participation (ie, in both scenarios, their years of participation were recorded as 1). Therefore, we used 2 years of participation as the threshold for sport involvement, from which the following classifications of *sport specialized* and *multisport* were derived: athletes were labeled as *sport specialized* in the present study if they had ≥ 2 years of participation in 1 sport and fewer than 2 years of participation in any other sport and *multisport* if they had ≥ 2 years of participation in each of at least 2 sports. This classification scheme differed

Table 1. Distribution of Adolescent Female Sport-Specialized and Multisport Athletes by Sport

Sport(s)	No. of Athletes	
	Sport Specialized	Multisport
All	366	366
Basketball	169	175
Soccer	141	167
Volleyball	56	24

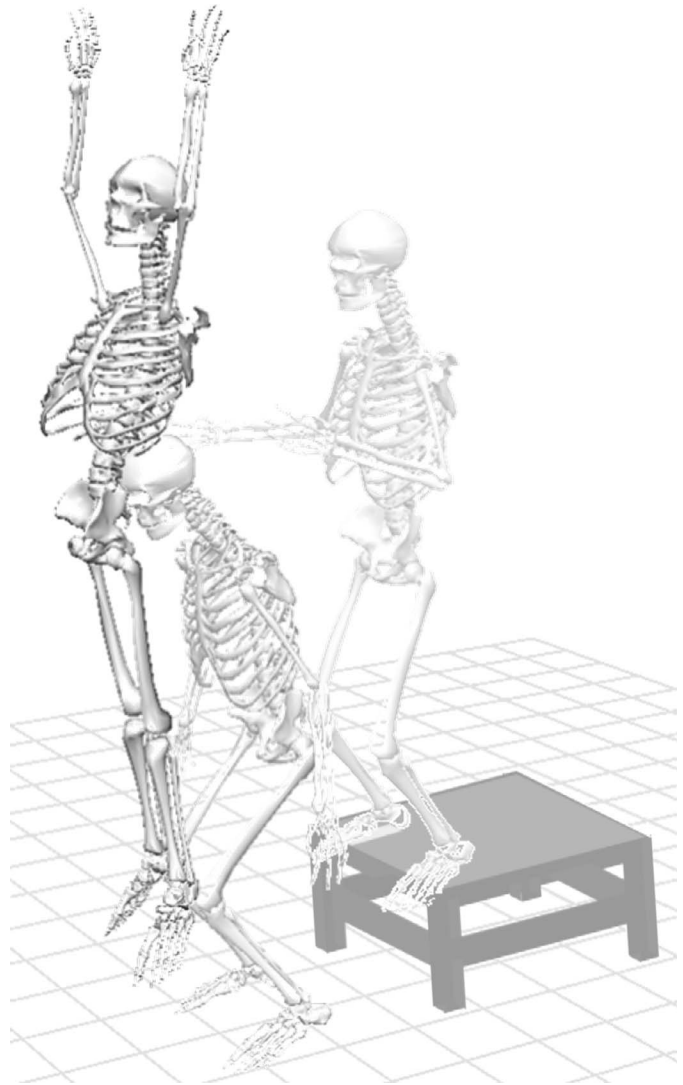


Figure 2. A representative participant performing the drop-vertical-jump task.

slightly from the one used by Hall et al,⁷ who considered all single-sport athletes—regardless of the number of years they participated—as sport specialized and all athletes who competed in more than 1 sport as multisport athletes. The distribution of sport-specialized and multisport athletes by sport is shown in Table 1.

Data Collection and Processing

Participants underwent a standard biomechanical assessment that included a minimum of 3 trials of the DVJ task from a 31-cm box (Figure 2). The DVJ was performed by first having participants align their feet with tape placed at the edge of the box and situated approximately shoulder-width apart. Participants were instructed to drop off the box with both feet at the same time, land in front of the box, and then immediately perform a maximum-effort vertical leap to reach a maximally positioned overhead target. Trials were repeated if participants did not leave the box with both feet at the same time or did not immediately perform a maximum vertical leap upon landing (ie, if they paused on landing and then jumped).

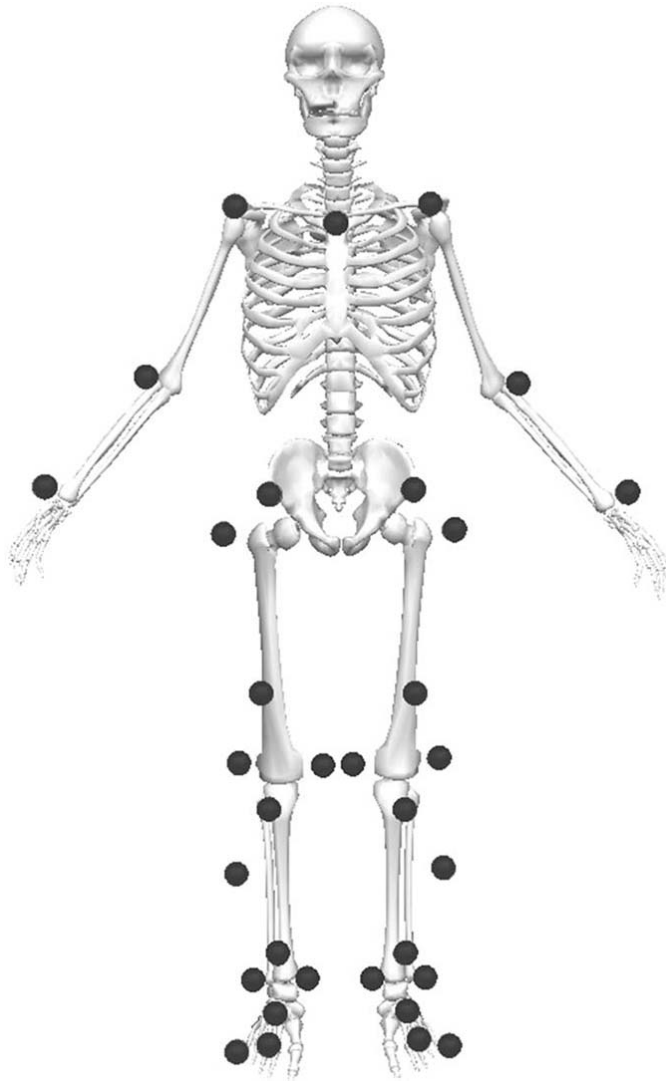


Figure 3. Anterior view of marker placement on a representative participant.

To perform the biomechanical analysis, participants were instrumented with 37 retroreflective markers; each segment possessed a minimum of 3 tracking markers. The same athletic trainer instrumented all participants. The athletic trainer palpated each participant for and affixed markers to specific anatomical landmarks: the lower back between the S5 and T1 vertebrae and bilaterally on the acromioclavicular joint, lateral epicondyle of the elbow, distal end of the forearm midway between the styloid processes of the radius and ulna, anterior-superior iliac spine, greater trochanter, medial and lateral femoral condyles, tibial tubercle, and medial and lateral malleoli. Additional tracking markers were placed on the anterior midthigh, lateral and anterior distal aspects of the shank, heel, dorsal surface of the midfoot, lateral foot (fifth metatarsal), and central forefoot (between the second and third metatarsals; Figure 3). All markers except those attached to the foot were affixed directly to the skin; the foot markers were affixed to the participants' own shoes with adhesive tape. A 10-camera, high-speed, passive optical motion-analysis system (Motion Analysis Corp, Santa Rosa, CA) sampling at 240 Hz was used to capture the 3-dimensional marker trajectory data

from each participant. After marker placement, a static trial was conducted with the participant in anatomical pose and foot direction and placement standardized to the laboratory's global coordinate system, followed by the DVJ trials.

Marker trajectories were filtered using a low-pass, fourth-order Butterworth filter with a cutoff frequency of 12 Hz. A 6-degrees-of-freedom skeletal model was applied to the filtered trajectories to determine the position and orientation of each segment at each time sample, and the model was scaled to each participant's height and weight. Cardan joint angles were calculated using Visual3D (C-Motion Inc, Germantown, MD) and were time normalized to 101 data points (representing 0%–100% of stance).

Data Analysis

A modified vector-coding technique^{24,25} was used to quantify interjoint coordination for various joint couplings during the stance phase of the DVJ. Specifically, the following joint couplings were examined: hip flexion and knee flexion, knee flexion and ankle flexion, hip flexion and knee abduction, knee flexion and knee abduction, knee flexion and knee internal rotation, and knee abduction and knee internal rotation. Coordination was quantified for a given joint coupling by first calculating a *coupling angle*, which indicates the relative angular motion within the coupling. Coupling angles for each of the examined joint couplings were determined for each participant's dominant and nondominant legs separately. See the Appendix for additional details on coupling-angle calculations.

After determining the coupling angles, we quantified intraparticipant coordination variability for each of the examined joint couplings by calculating the coupling-angle variability (CAV)²⁶ across each participant's DVJ trials (see Appendix). The CAV was interpreted as the variation in participants' landing strategies for each of the examined couplings; specifically, this quantified how variable each joint's angular motion was relative to the other in a given coupling across iterations of the DVJ task. The calculation of coupling angle and CAV for the hip-flexion and knee-flexion joint coupling of a representative participant is provided in Figure 4. The average CAV values for each joint coupling during the landing phase of stance were submitted for statistical analysis.

Statistical Analysis

Independent *t* tests were used to identify differences in anthropometric and self-reported measures of sport participation between the sport-specialized and multisport groups, and the Cohen *d* was used to calculate effect sizes between the groups for each measure. The variability of each of the examined joint couplings was submitted to separate general linear models and was evaluated for between-participants differences in both group (ie, sport specialized versus multisport) and pubertal status (ie, prepubertal and midpubertal versus postpubertal) using 2×2 analyses of variance. Pubertal status was included as a factor in the model to examine the potential interaction of maturation and sport-specialization status on joint variability. The dominant and nondominant limbs were assessed separately. An α level of .05 was selected a priori to indicate statistical significance.

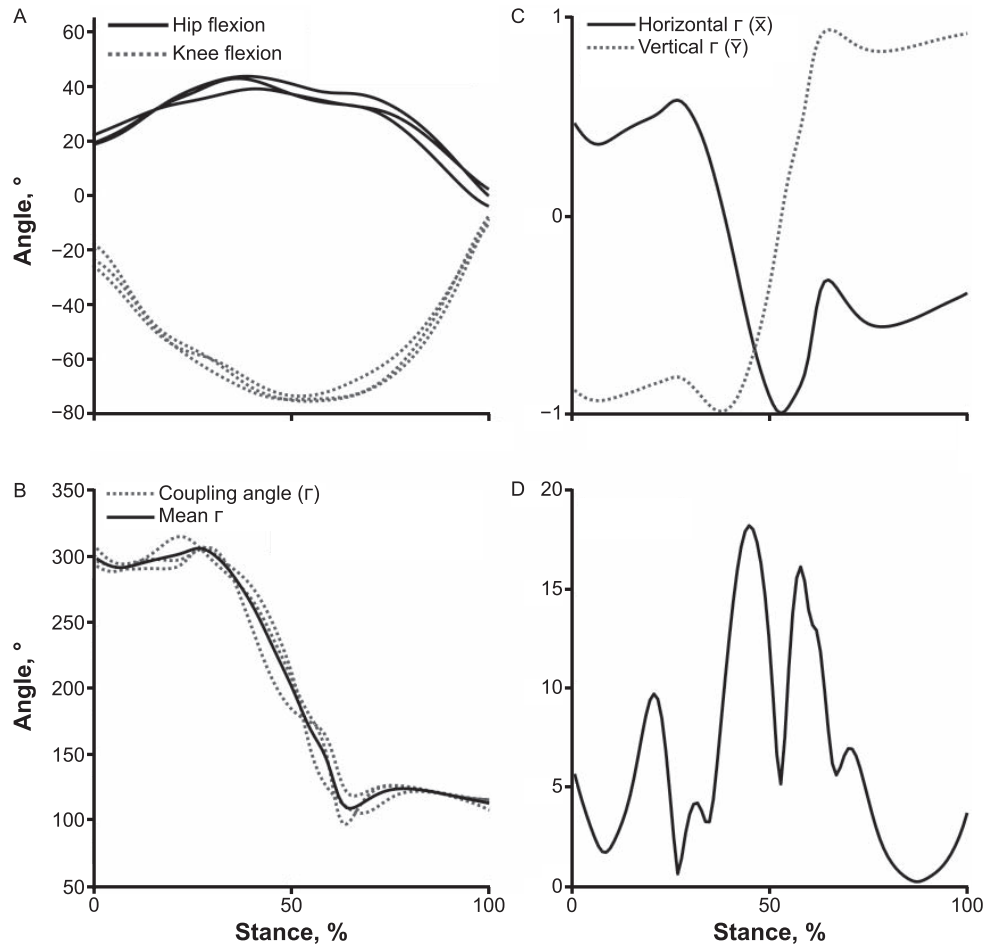


Figure 4. An illustration of the coupling-angle-variability (CAV) calculation for the hip-flexion/knee-flexion joint coupling for a representative participant. The top left shows hip and knee flexion across 3 drop-vertical-jump (DVJ) trials; the bottom left shows the coupling angle (γ) for the DVJ trials and the mean angle; the top right shows the mean horizontal (\bar{x}) and vertical (\bar{y}) components of the mean coupling angle; the bottom right shows the CAV.

RESULTS

The summary anthropometric and sport-participation measures recorded for all participants are illustrated in Table 2. The sport-specialized and multisport groups did not differ in height, weight, body mass index, or body fat percentage (all P values $> .05$); however, the sport-specialized group had, on average, slightly more years of self-reported sport participation ($P = .002$) than the multisport group. Subsequently, we conducted post hoc analyses of covariance for each general linear model using average years of sport participation as a covariate.

The average CAV measures among both the sport-specialized and multisport groups for each joint coupling are shown in Figure 5. Specifically, the analyses of covariance revealed a significant main effect of group on the dominant limb, with individuals in the sport-specialized group exhibiting increased variability in the hip-flexion and knee-flexion ($F_{1,724} = 6.01$, adjusted $P = .015$, $\eta^2 = 0.010$) and knee-flexion and knee-abduction ($F_{1,724} = 6.17$, adjusted $P = .014$, $\eta^2 = 0.010$) coupling, as well as slightly increased variability in the knee-flexion and knee-internal-rotation coupling ($F_{1,724} = 3.99$, adjusted $P = .048$, $\eta^2 = 0.007$). No differences were evident between groups on any

Table 2. Summary and Statistical Measures of Recorded Anthropometric and Self-Reported Sport-Participation Data for Female Adolescent Sport-Specialized and Multisport Athletes

Measure	Sport Specialized			Multisport			P Value	t Value	d Value
	Minimum	Maximum	Mean \pm SD	Minimum	Maximum	Mean \pm SD			
Age, y	11.0	21.3	14.0 \pm 2.0	11.0	21.3	13.6 \pm 1.9	.002 ^a	3.129	0.327
Height, cm	144.0	180.3	160.9 \pm 6.6	143.5	182.9	160.5 \pm 6.7	.435	0.780	0.082
Weight, kg	35.1	89.9	55.2 \pm 10.2	34.9	92.7	54.9 \pm 10.3	.646	0.459	0.048
Body mass index, kg/m ²	14.7	33.0	21.3 \pm 3.2	14.3	32.1	21.2 \pm 3.4	.910	0.113	0.012
Body fat, %	5.8	44.6	24.2 \pm 7.0	4.7	42.2	24.3 \pm 7.3	.889	0.140	0.015
Sport participation, y	2.0	18.0	5.9 \pm 3.2	2.0	15.0	5.2 \pm 2.1	.002 ^a	3.174	0.332

^a Indicates statistical significance.

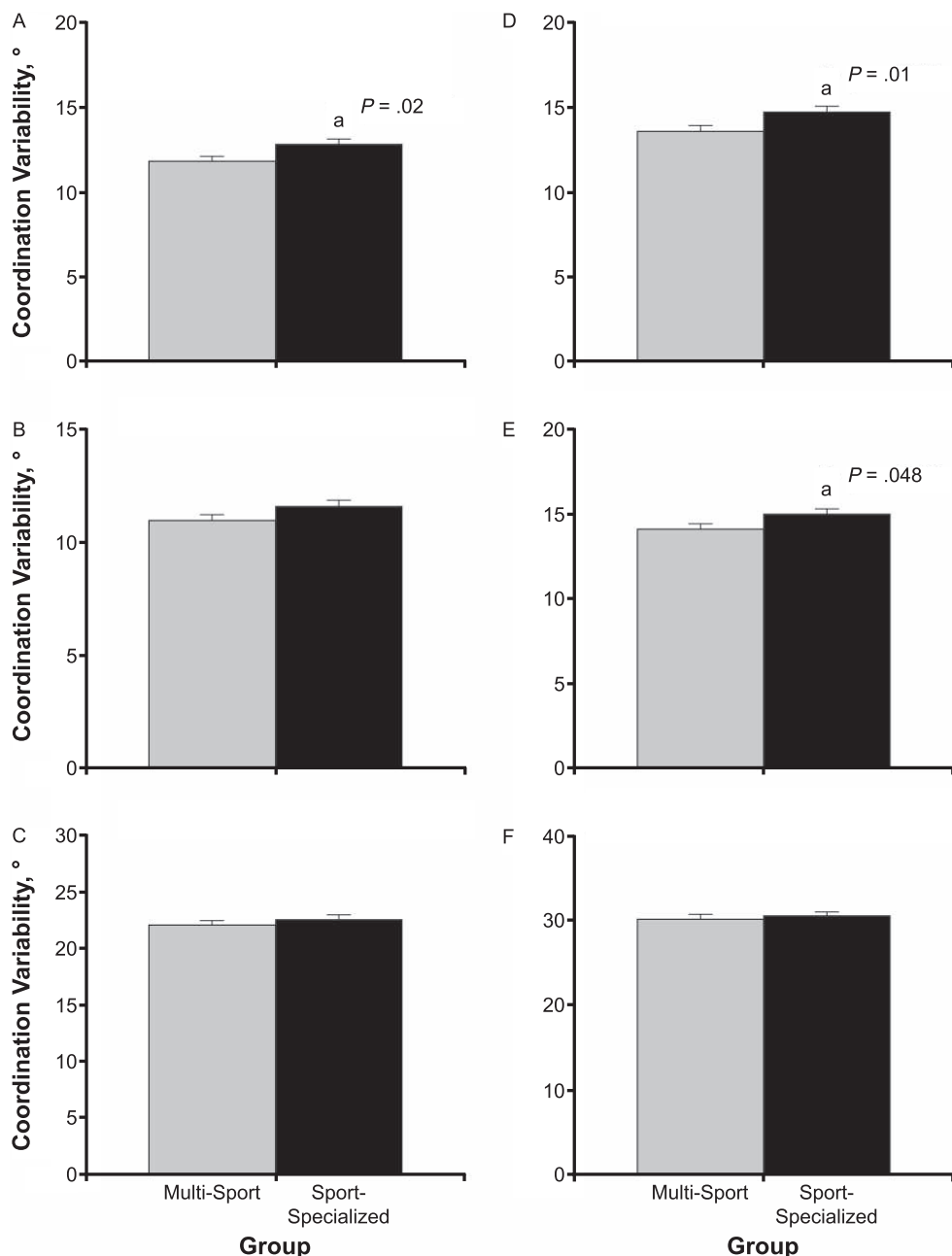


Figure 5. Average coupling-angle-variability measures for each of the examined joint couplings between the multisport and sport-specialized athletes. The error bars represent standard errors between the groups. ^a Indicates statistical significance.

of the other CAV measures for the dominant limb, and no differences were found for the nondominant limb on any CAV measures (all P values $> .05$). In addition, no significant group \times maturation interactions were present for any of the examined joint couplings or for years of sport participation (all P values $> .05$).

DISCUSSION

The purpose of our study was to examine how coordination patterns varied among female adolescent sport-specialized and multisport athletes for key joint couplings that underlie musculoskeletal injury. We used a modified vector-coding technique to examine intra-athlete coordination variability during DVJ performance between

sport-specialized and multisport adolescent female basketball, soccer, and volleyball athletes; the latter exhibited evidence of potentially altered variability in the coordination between sagittal-plane hip and knee motion, as well as between sagittal-plane knee motion and frontal-plane knee motion in the dominant limb. Specifically, sport-specialized athletes exhibited higher variability for these couplings, which may represent less stable hip-coordination and knee-coordination patterns during landing and may ultimately lead to less efficient or more risky biomechanical outcomes.

For youth athletes, especially prepubertal or pubertal athletes, the musculoskeletal and physiological immaturity that may result from nonlinear and sporadic growth in bone mineral density and muscular and connective tissue strength²⁷ may equip them less optimally to handle

continual, nonvariable, or repetitive stresses (or a combination of these) that may result from single-sport participation than mature or adult athletes. Sport-specialized athletes exhibited increased variability in joint couplings (ie, hip flexion and knee flexion and knee flexion and knee abduction) of the dominant limb that are mechanistically involved in effectively landing from a jump. Effective landing necessitates coordinated sagittal-plane hip-joint and knee-joint angular motion, driven by a proximal hip neuromuscular-control mechanism, that modulates ground reaction forces on landing²⁸; slightly altered coordination strategies that involve the hip or knee joints (or both) may affect this mechanism and lead to unstable landings, inefficient force-absorption strategies, or greater contact forces that can place the lower extremities at risk for injury. Interestingly, the lack of interaction of maturation and group indicated that these coordinative differences were present regardless of maturation level; this presents implications for prepubertal adolescent athletes, particularly girls, whose coordinative alterations may be compounded by compromised neuromuscular control and aberrant biomechanical patterns that accompany growth and maturation and that underlie an increased risk of injury, such as anterior cruciate ligament tear.²⁹ Accordingly, why these same alterations were not present in the nondominant limb and how coordinative differences between dominant and nondominant limbs may affect biomechanical outcomes were unclear. We speculate that coordination deficits due to early specialization may be more likely to occur in the dominant limb, which is the driver of skill-based movements in isolated and repetitive sport performance. Future studies that examine the associations between coordinative structures and biomechanical and neuromuscular patterns associated with limb dominance are warranted to explore these links further.

For athletic trainers and other health care practitioners, future work should be devoted to the development of clinically based tools that are sensitive to coordinative differences, as well as training and rehabilitation tools and protocols designed to improve them, such as proprioceptive, agility, and other neuromuscular-training techniques. The ability to detect coordination differences early using simple clinical tools may allow athletic trainers to tailor interventions that reduce the risk of lower extremity injury not only in early specialized athletes but in all athletes. Any new clinical tools must also detect changes in coordination to ensure that newly developed rehabilitation protocols and neuromuscular-training techniques are effective for improving neuromuscular performance. The development and assessment of such tools and techniques may help to mitigate the deficits that arise from single-sport participation.

The coordinative deficits identified in the early-specialized young athletes in the current study may increase their risk for injury. Young athletes who specialize early (eg, before maturation) in a single sport may have limited potential for motor-skill and coordination development.³⁰ This can result when they do not participate in as much unstructured free play or daily physical education as their peers. Without opportunities for sport diversification during their growing years, young athletes may not fully develop the neuromuscular-coordination patterns that can protect against injury.^{22,31,32} Although the current evidence indi-

cated that all youths should be involved in periodized strength and conditioning (eg, integrative neuromuscular training) to help them prepare for the demands of competitive sport participation,^{33,34} youths who specialize in a single sport should deliberately plan for periods of isolated (eg, planned off-seasons) and focused integrative neuromuscular training to enhance diverse motor-skill development and help reduce the potential for coordinative deficits.^{35–37}

An understanding of the influence of sport specialization on coordination patterns has practical implications for how and when adolescent athletes can safely specialize in sport. If adopted at an appropriate time during maturation, sport specialization can lead to skill improvement and refinement in that sport and, subsequently, greater potential for achievement.^{12,13} However, a lack of established criteria for identifying “early” sport specialization makes this determination difficult. *Early sport specialization* has a variety of definitions and, currently, no consensus exists on a definition or the training volume to quantify it. Baker et al³⁸ noted that early specialization entailed an early start to a specific sport, early involvement in only 1 sport, early involvement in high-intensity sport training, and early involvement in competition. Côté et al³⁹ defined early sport specialization as a focus on 1 sport in childhood through many hours of deliberate practice with the goal of improving sport performance. Other similar definitions may build upon the notion of early and frequent participation in 1 sport year-round from a young age.^{5,40} However, these definitions do not capture training volume in months per year, sessions per month or week, hours per session of training, or time off from training and competition. They also do not specify what age or maturation level is considered “early.” The demands of sport, especially individual sports, such as gymnastics and tennis, sometimes require athletes to specialize early. Consequently, athletes in these sports are more likely to specialize at an earlier age than athletes in team sports and, as a result, accrue more overuse injuries. Determining when an athlete can and should specialize in a single sport and identifying athletes at risk for significant physical or mental health impairments are critical needs for practitioners, parents, coaches, and athletes themselves. Thus, coordination assessment may help to identify athletes at risk for specializing in sport too early; differentiating sport-specialized athletes based on coordinative outcomes may facilitate this determination.

A limitation in the present study was the definition of *sport specialization* used to differentiate the athletes. As previously mentioned, mere participation in a single sport does not necessarily indicate sport specialization; therefore, we were unsure whether the sport-specialized athletes identified in the present study were truly sport specialized. Our definition of sport specialization differed slightly from that used in previous work⁷; however, this was the result of ambiguity in the questionnaire that was administered to the athletes to establish sport-specialization status. Future researchers who associate coordinative or biomechanical implications of sport specialization should establish the precise degree to which athletes are sport specialized, that is, participating in a sport year-round to the exclusion of others. This can be more fully determined using a nonbinary scale: for example, classifying athletes as having

low, medium, or high levels of sport specialization status^{6,8} as opposed to grouping athletes as specialized or multi-sport. In addition, the coordinative alterations we observed should be interpreted with caution, as the effect sizes for hip flexion and knee flexion, knee flexion and knee abduction, and knee flexion and knee internal rotation ($\eta^2 = 0.010, 0.010, \text{ and } 0.007$, respectively) were small⁴¹; however, this may be due in part to the inherent subjectivity associated with the definition of *early sport specialization* we used. Future investigators should also aim to clarify the definition by including sport-specific and age-related or maturation-related criteria. Another limitation of this study was the lack of standardized footwear worn by participants performing the DVJ. Differences in shoe type or structure may alter loading during landing and jumping tasks, which may subsequently elicit more variable movement patterns or coordinative strategies. Future authors should standardize the footwear worn by participants to minimize undesirable variations in task performance. In addition, because a given testing session represented a participant's first visit to the laboratory, it is likely that many of these athletes had no prior experience with the DVJ and, subsequently, they may have been uncomfortable with the motion-analysis process or the presence of teammates and coaches during assessment. Other factors (for example, the potential influence of menstrual status on joint laxity⁴²) could have also affected task performance. Although we took great care to minimize the potential confounding effects of these factors, they could ultimately have affected task performance.

CONCLUSIONS

Sport specialization, particularly at an early age, can lead to physical and mental detriments that place youths at risk for injury and other negative sport outcomes, which may lead to eventual sport cessation and inactivity.⁴³ Although an exclusive commitment to a single sport year-round may result in overuse injury in many young athletes, coordinative differences possibly associated with sport specialization can exacerbate this likelihood. We found that earlier sport specialization was associated with increased variability in the between-joints coupling at the hip and knee in the sagittal plane. At the knee joint, where female athletes are particularly susceptible to aberrant mechanics and injury risk, the sport-specialized athletes demonstrated increased variability between sagittal-plane and frontal-plane and transverse-plane coordination. Altered landing strategies resulting in increased variability of coordination of the hip and knee joints may underlie unstable landings, inefficient force-absorption strategies, or greater contact forces (or a combination of these) that can place the lower extremities at risk for injury. Future research into coordination measures and their association with biomechanical injury risk in young female athletes is warranted.

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REFERENCES

- DiFiori JP, Benjamin HJ, Brenner JS, et al. Overuse injuries and burnout in youth sports: a position statement from the American Medical Society for Sports Medicine. *Br J Sports Med.* 2014;48(4):287–288.
- Malina RM. Early sport specialization: roots, effectiveness, risks. *Curr Sports Med Rep.* 2010;9(6):364–371.
- Brenner JS; American Academy of Pediatrics Council on Sports Medicine and Fitness. Overuse injuries, overtraining, and burnout in child and adolescent athletes. *Pediatrics.* 2007;119(6):1242–1245.
- Gould D. The professionalization of youth sports: it's time to act! *Clin J Sport Med.* 2009;19(2):81–82.
- Jayanthi N, Pinkham C, Dugas L, Patrick B, Labella C. Sports specialization in young athletes: evidence-based recommendations. *Sports Health.* 2013;5(3):251–257.
- Jayanthi NA, LaBella CR, Fischer D, Pasulka J, Dugas LR. Sports-specialized intensive training and the risk of injury in young athletes: a clinical case-control study. *Am J Sports Med.* 2015;43(4):794–801.
- Hall R, Barber Foss K, Hewett TE, Myer GD. Sport specialization's association with an increased risk of developing anterior knee pain in adolescent female athletes. *J Sport Rehabil.* 2015;24(1):31–35.
- McGuine TA, Post EG, Hetzel SJ, Brooks MA, Trigsted S, Bell DR. A prospective study on the effect of sport specialization on lower extremity injury rates in high school athletes. *Am J Sports Med.* 2017;45(12):2706–2712.
- Post EG, Trigsted SM, Riekema JW, et al. The association of sport specialization and training volume with injury history in youth athletes. *Am J Sports Med.* 2017;45(6):1405–1412.
- Pasulka J, Jayanthi N, McCann A, Dugas LR, LaBella C. Specialization patterns across various youth sports and relationship to injury risk. *Phys Sportsmed.* 2017;45(3):344–352.
- Olsen SJ 2nd, Fleisig GS, Dun S, Loftice J, Andrews JR. Risk factors for shoulder and elbow injuries in adolescent baseball pitchers. *Am J Sports Med.* 2006;34(6):905–912.
- Güllich A, Emrich E. Evaluation of the support of young athletes in the elite sports system. *Eur J Sport Soc.* 2006;3(2):85–108.
- Carlson R. The socialization of elite tennis players in Sweden: an analysis of the players' backgrounds and development. *Sociol Sport J.* 1988;5(3):241–256.
- Hulteen RM, Morgan PJ, Barnett LM, Stodden DF, Lubans DR. Development of foundational movement skills: a conceptual model for physical activity across the lifespan. *Sports Med.* 2018;48(7):1533–1540.
- Hamill J, van Emmerik RE, Heiderscheit BC, Li L. A dynamical systems approach to lower extremity running injuries. *Clin Biomech (Bristol, Avon).* 1999;14(5):297–308.
- Cunningham TJ, Mullineaux DR, Noehren B, Shapiro R, Uhl TL. Coupling angle variability in healthy and patellofemoral pain runners. *Clin Biomech (Bristol, Avon).* 2014;29(3):317–322.
- Pollard CD, Stearns KM, Hayes AT, Heiderscheit BC. Altered lower extremity movement variability in female soccer players during side-step cutting after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2015;43(2):460–465.
- Gribbin TC, Slater LV, Herb CC, et al. Differences in hip-knee joint coupling during gait after anterior cruciate ligament reconstruction. *Clin Biomech (Bristol, Avon).* 2016;32:64–71.
- Turvey MT. Coordination. *Am Psychol.* 1990;45(8):938–953.
- Handford C, Davids K, Bennett S, Button C. Skill acquisition in sport: some applications of an evolving practice ecology. *J Sports Sci.* 1997;15(6):621–640.

21. Bartlett R, Wheat J, Robins M. Is movement variability important for sports biomechanists? *Sport Biomech.* 2007;6(2):224–243.
22. Hewett TE, Myer GD, Kiefer AW, Ford KR. Longitudinal increases in knee abduction moments in females during adolescent growth. *Med Sci Sports Exerc.* 2015;47(12):2579–2585.
23. Hewett TE, Ford KR, Xu YY, Khoury J, Myer GD. Effectiveness of neuromuscular training based on the neuromuscular risk profile. *Am J Sports Med.* 2017;45(9):2142–2147.
24. Sparrow WA, Donovan E, van Emmerik R, Barry EB. Using relative motion plots to measure changes in intra-limb and inter-limb coordination. *J Mot Behav.* 1987;19(1):115–129.
25. Chang R, van Emmerik R, Hamill J. Quantifying rearfoot-forefoot coordination in human walking. *J Biomech.* 2008;41(14):3101–3105.
26. Vidal A, Wu W, Nakajima M, Becker J. Investigating the constrained action hypothesis: a movement coordination and coordination variability approach. *J Mot Behav.* 2018;50(5):528–537.
27. Hawkins D, Metheny J. Overuse injuries in youth sports: biomechanical considerations. *Med Sci Sports Exerc.* 2001;33(10):1701–1707.
28. Pollard CD, Sigward SM, Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clin Biomech (Bristol, Avon).* 2010;25(2):142–146.
29. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* 2005;33(4):492–501.
30. Myer GD, Jayanthi N, DiFiori JP, et al. Sport specialization, part I: does early sports specialization increase negative outcomes and reduce the opportunity for success in young athletes? *Sports Health.* 2015;7(5):437–442.
31. Ford KR, Myer GD, Hewett TE. Longitudinal effects of maturation on lower extremity joint stiffness in adolescent athletes. *Am J Sports Med.* 2010;38(9):1829–1837.
32. Ford KR, Shapiro R, Myer GD, Van Den Bogert AJ, Hewett TE. Longitudinal sex differences during landing in knee abduction in young athletes. *Med Sci Sports Exerc.* 2010;42(10):1923–1931.
33. Faigenbaum AD, Myer GD, Farrell A, et al. Integrative neuromuscular training and sex-specific fitness performance in 7-year-old children: an exploratory investigation. *J Athl Train.* 2014;49(2):145–153.
34. Faigenbaum AD, Lloyd RS, MacDonald J, Myer GD. Citius, altius, fortius: beneficial effects of resistance training for young athletes: narrative review. *Br J Sports Med.* 2016;50(1):3–7.
35. Myer GD, Faigenbaum AD, Ford KR, Best TM, Bergeron MF, Hewett TE. When to initiate integrative neuromuscular training to reduce sports-related injuries and enhance health in youth? *Curr Sports Med Rep.* 2011;10(3):157–166.
36. Myer GD, Faigenbaum AD, Chu DA, et al. Integrative training for children and adolescents: techniques and practices for reducing sports-related injuries and enhancing athletic performance. *Phys Sportsmed.* 2011;39(1):74–84.
37. Myer GD, Jayanthi N, DiFiori JP, et al. Sports specialization, part II: alternative solutions to early sport specialization in youth athletes. *Sports Health.* 2016;8(1):65–73.
38. Baker J, Cogley S, Fraser-Thomas J. What do we know about early sport specialization? Not much! *High Abil Stud.* 2009;20(1):77–89.
39. Côté J, Lidor R, Hackfort D. ISSP position stand: to sample or to specialize? Seven postulates about youth sport activities that lead to continued participation and elite performance. *Int J Sport Exerc Psychol.* 2009;7(1):7–17.
40. Hill G. *A Study of Sport Specialization in Midwest High School Athletes* [dissertation]. Iowa City: University of Iowa; 1987.
41. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates; 1988.
42. Zazulak BT, Paterno M, Myer GD, Romani WA, Hewett TE. The effects of the menstrual cycle on anterior knee laxity: a systematic review. *Sports Med.* 2006;36(10):847–862.
43. Andrew N, Wolfe R, Cameron P, et al. The impact of sport and active recreation injuries on physical activity levels at 12 months post-injury. *Scand J Med Sci Sports.* 2014;24(2):377–385.

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Appendix. Calculation of Coupling-Angle Variability

Coupling-angle variability (CAV) can be used to assess underlying coordination during task performance and may help to elucidate differences in coordinative processes. To compute this variability, the coupling angle between 2 joints must first be calculated across multiple iterations of a given task. We determined the coupling angle for each joint coupling during the stance phase for each of the 3 drop-vertical-jump (DVJ) trials performed by the participants. This angle was computed for each percentage (ie, 0%–100%) of stance as the angle formed by the right horizontal and a vector joining successive pairs of points on an angle-graph, calculated as

$$\gamma_i = \tan^{-1} \left(\frac{y_{i+1} - y_i}{x_{i+1} - x_i} \right),$$

where γ_i is the coupling angle, bound between 0° and 360°.

After this, CAV was computed across each participant's DVJ trials. At each percentage of the landing phase, the mean horizontal (\bar{x}) and vertical components (\bar{y}) of the coupling angle across j DVJ trials were calculated respectively as

$$\bar{x} = \frac{1}{n} \sum_{j=1}^n \cos \gamma_j;$$

$$\bar{y} = \frac{1}{n} \sum_{j=1}^n \sin \gamma_j;$$

from which CAV at each percentage of stance was calculated as

$$CAV_i = \sqrt{2 \times \left(1 - (\bar{x}_i^2 + \bar{y}_i^2)^{\frac{1}{2}} \right)} \times \frac{180}{\pi}.$$

Only CAV during the landing phase of stance was considered. In the present study, the landing phase was defined as the period of time from when participants made initial contact with the ground until their center of mass (COM) reached a minimum vertical height. The COM of each model was computed at each time sample in Visual3D (C-Motion Inc, Germantown, MD) as the weighted summation of the COM of 12 model segments (ie, 2 × foot, 2 × shank, 2 × thigh, pelvis, trunk/head, 2 × upper arm, 2 × forearm/hand):

$$\text{COM} = \frac{\sum_{i=1}^{12} m_i r_i}{M},$$

where m_i is the mass of the i th segment, r_i are the 3-dimensional coordinates, and M is the total body mass. Because CAV was computed over multiple DVJ trials, the average vertical trajectory of the COM from all trials was computed, from which the minimum vertical height that marked the end of the landing phase for the participant was detected.