Differences in Segmental Coordination and Postural Control in a Multi-joint Dance Movement

Développé Arabesque

Shaw Bronner, P.T., Ph.D., O.C.S.

Abstract

Analysis of skill at multiple points on the learning continuum provides insight into how complex limb and postural organization is modified with extended practice. Dancers at three skill levels were compared performing a domain-specific movement (développé arabesque) to identify motor control parameters underlying skill acquisition of a sequential multi-joint trunk and extremity movement. It was hypothesized that general organization would be similar between groups, but that segmental coordination and postural control would differ with skill level. Twenty-seven expert, advanced, and intermediate dancers performed six repetitions of an arabesque sequence with the right limb. Data were acquired with a five-camera motion analysis system. Differences between groups in pelvis and gesture limb displacement, joint coordination patterns, and variability were determined using ANOVA with post hoc comparisons where applicable. Subjects displayed similar movement organization and timing. Differences were found in postural pelvic control and intra- and inter-limb coordination. These differences were most apparent during the arabesque phase. Control of the pelvis appears to be a key area that requires prolonged practice to master.

What distinguishes expert performance of a motor task from that of the beginner or advanced performer? Studies indicate that skilled performers demonstrate movement skills that are more effective, efficient, and consistent during general as well as domain-specific movements. (Note: "consistency" may be determined by achievement of the movement goal, although movement strategies and joint organization may co-vary to optimize the task outcome.) They accomplish this through strategies of limb segment and postural coordination that differ from those of less trained subjects, tailored to maximize success of the movement goal.[1-16] Based on data from a variety of domains (music, mathematics, chess, sports, and dance), it has been estimated that individuals require prolonged, deliberate practice of ten years or more to attain exceptional levels of performance.[17]

Analyses of motor skills often focus on a moving (i.e., gesture or focal) limb alone, and do not consider postural control,[10,13] or vice versa.[5] However, situations in which only a part of the body is moved voluntarily, such as simply lifting a limb, may differ in response characteristics from situations where there is coordinated arm, leg, and trunk movement with a balance requirement. Different postural coordination patterns following training have been reported in gymnastics; trained gymnasts execute backward bending movements with lower horizontal excursion of the center of mass more rapidly than do naïve subjects.[18]

Comparison of different levels of skill at opposite extremes of the learning spectrum (novices and experts) permits use of a time scale of practice that is, perhaps, more realistic than those of early learning alone. Rarely studied are the shifts in coordination that may occur later in practice. Analysis of skill acquisition at multiple points on the learning curve (intermediate, advanced, and expert) in sequences that incorporate gesture (focal) limb with whole body movement may provide insight into how complex limb and postural organization is modified with extended practice across the learning continuum.

Dance training incorporates highly specific movements that require precise spatial and temporal coordination of postural control with multi-joint limb movement to achieve a performance aesthetic. Unlike other multi-joint limb movements, such as kicking a ball with an external accuracy requirement (e.g., through the goalposts), the intention of a dance

Shaw Bronner, P.T., Ph.D., O.C.S., is the Director of the ADAM Center, Long Island University, Brooklyn, New York, and the Director of Physical Therapy Services at Alvin Ailey, New York, New York.

Correspondence: Shaw Bronner, P.T., Ph.D., O.C.S., ADAM Center, Long Island University, One University Plaza LLC6, Brooklyn, New York 11215; sbronner@liu.edu.

movement is the shape and timing of the movement itself. Since dancers at all skill levels practice the same movements, they are an ideal population for the study of changes in the coordination of movement with extended practice.

In this exploratory study, dancers at three levels of training were compared performing a domain-specific movement (développé arabesque) to 1. describe the kinematics of the movement sequence, and 2. identify the coordination parameters underlying performance of this sequential multijoint trunk and extremity movement. It was hypothesized that general organization (e.g., overall shape and timing of the gesture hip, knee, and ankle angular displacement), mastered relatively quickly, would be similar for each group. Additionally, segmental coordination and postural control would differ with skill level, demonstrated by intra-segmental (e.g., hip, knee, and ankle) and inter-segmental (e.g., toe and finger) temporal coordination, control of pelvic motion (e.g., range and consistency of pelvic angular and linear displacement), and consistency of balance control.

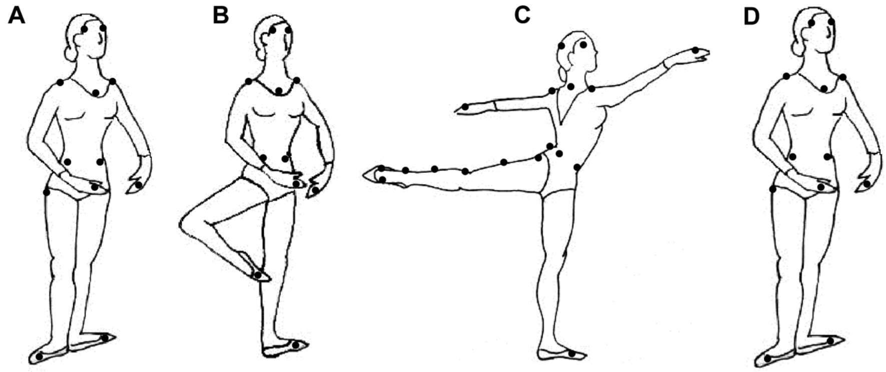

Figure 1 Arabesque sequence: **A**, first position, **B**, passé, **C**, arabesque, and **D**, first position.

Methods
Subjects

Twenty-seven healthy adult dancers, recruited from one international pre-professional dance school and company, volunteered for this study. Each dancer was assigned to one of three distinct levels of dance training (intermediate, advanced, or expert), resulting in three groups of nine subjects each. Intermediate (INT) and advanced (ADV) groups were based on class placement by dance faculty through annual audition. Expert (EXP) level was based on employment in a professional company, indicating that through the audition process they had achieved exemplary status. Only dancers who could attain arabesque at a height of 90° (gesture limb parallel to the floor) were included (Fig. 1C). Those with a history of lower extremity injury during the previous 6 months that caused them to stop dancing for one week or more were excluded. The study was approved by the university's Institutional Review Board.

Each dancer's height and leg length was measured. Age, number of years dancing, and gender were recorded. Preferred first position turnout for each dancer was quantified by measuring the angle formed by a line drawn from each second toe to a center point between the heels.[19,20] Means (± SE) were calculated for all demographic variables, and ANOVA was used to compare group data ($p < 0.05$). EXP dancers were older (24.9 ± 1.0 years) than ADV and INT dancers (19.6 ± 0.5 and 19.8 ± 0.5 years, respectively; $p < 0.001$; Table 1). EXP and ADV subjects had danced an average of twice as long (13.3 ± 1.9 and 11.7 ± 1.1 years) as INT dancers (6.1 ± 1.6 years; $p < 0.02$). There were no differences between groups in height, leg length, or first position turnout.

Instrumentation

Three-dimensional (3-D) kinematic data were collected at a sampling rate of 120 Hz, with a five-camera motion analysis system (Vicon 250, Oxford Metrics Ltd, Oxford, UK). A full body marker set comprised of 29 reflective, spherical markers was used to create an 11-segment model (Fig. 1). Reflective markers were placed bilaterally at the superior orbit, occiput, acromion process, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), greater trochanter, lateral mid-femur, lateral knee joint line (knee), lateral mid-calf, lateral malleolus (ankle), first metatarsal-phalangeal joint (toe), fifth metatarsal-phalangeal joint, and second metacarpal-phalangeal joint (finger), and unilaterally at the sternal notch, seventh cervical vertebra spinous process, and left scapula.

The pelvis formed a rigid segment created by the two ASIS and two

Table 1 Demographics: Mean (SE)

	Expert	Advanced	Intermediate
Gender	5 males and 4 females	2 males and 7 females	4 males and 5 females
Height (m)	1.71 (0.04)	1.71 (0.03)	1.72 (0.01)
Leg length (m)	0.91 (0.02)	0.93 (0.02)	0.93 (0.01)
Age (years)	24.9 (1.0)	19.6 (0.5)	19.8 (0.5)*
Years dancing	13.3 (1.9)	11.7 (1.1)	6.1 (1.6)*
First position (deg)	109.3 (2.2)	117.7 (4.9)	106.6 (3.7)

*ANOVA ($p < 0.02$): Age and Years dancing.

PSIS markers. Pelvic movement, with respect to the global reference in x, y, and z axes, was defined as pelvic obliquity (side bending around the x-axis), pelvic tilt (anterior-posterior motion around the y-axis), and pelvic transverse rotation (rotation around the longitudinal z-axis).[21] Pelvic translation was defined as linear displacement in the frontal plane, or y-direction.

Joint motion of the extremities was locally referenced to the body. Hip, knee, and ankle angular displacements were calculated with respect to a local reference with Euler angle conventions using the following sequence of rotations: flexion and extension about the y-axis of the proximal segment; adduction and abduction about a floating x-axis; followed by internal and external rotation about the z-axis of the distal segment.[22] By convention, hip and knee extension and ankle plantar flexion in the sagittal plane were denoted as negative in all histographs.

Experimental Protocol

The dance-specific task selected for study, développé arabesque, is a sequential, multi-joint movement that requires coordinated lower and upper extremity movement with unipedal postural control, is practiced in every ballet class, and consequently was well known to each subject. Développé arabesque primarily occurs in the sagittal plane: as the lower extremity extends posteriorly at a 90° angle to the stance limb, the trunk must shift anteriorly. The spine is arched in extension (bent backward) as the gesture hip is extended, creating the image of an arc from the head to the toe of the gesture foot (Fig. 1C). Each dancer's preferred first position foot placement (heels touching with lower extremities externally rotated) was marked on the floor and used as the starting position (Fig. 1A). The starting arm posture was designated as fifth position en bas[23] (arms form an oval shape in front of the dancer while hanging down; Fig. 1A). A marker was placed 1.5 m above the floor on the wall in front of the subject to standardize the subjects' visual focus.

A tape recording of a metronome with voice instruction overlay provided the tempo of the movement sequence (40 beats/min). Subjects practiced the arabesque sequence—first position, passé, arabesque, return (to first position) (Fig. 1)—prior to data acquisition to synchronize their movements with the metronome. From the starting posture (first position), the gesture leg passed through passé (hip and knee flexion with ankle plantar flexion), and extended posteriorly to arabesque (gesture hip and knee extension with ankle plantar flexion), where it was held for one count, followed by return to the initial position. The port de bras (movement of the upper extremities) correspondingly moved from fifth position en bas (arms hanging down in oval shape), to first position (arms held in oval shape at the level of the xiphoid process), then to second arabesque (gesture arm, ipsilateral to the gesture leg, is forward), followed by return to the initial position.

During practice, subjects were instructed to emphasize spatial and temporal precision. Specifically, they were asked to reach the height of the passé on the count of "one" (bringing the gesture toe to the level of the stance knee medial joint line), achieve a 90° arabesque on "two," hold this position until "three," and return the foot to first position on the floor on the count of "four." Subjects performed six consecutive trials with the right limb as gesture limb. One 6-trial condition was approximately 40 seconds in length.

Attire for all subjects consisted of a dark colored unitard to maximize contrast of reflective markers.

Data Analysis

Kinematic data were reconstructed using Vicon Workstation software (Oxford Metrics, Ltd., Oxford, UK) and filtered with a 4th order zero lag low pass Butterworth filter with a cutoff of 6 Hz. Movement onset and termination was defined as three consecutive increases or decreases respectively in displacement variables. Alternative onset and termination thresholds (5% of mean displacement and two SDs from mean baseline) produced qualitatively similar results. Dependent variables included pelvic angular displacement in each plane, pelvic translation in the frontal (y) plane, gesture limb (hip, knee, and ankle) sagittal angular displacement and velocity, and end-segment (right gesture toe and ipsilateral finger marker) resultant displacement and velocity.

To determine a temporal overview of movement organization, mean (± SE) onset and completion times of movement sequence and phase duration were calculated for pelvis, hip, knee, ankle, and toe variables. To determine a spatial overview of movement organization, mean (± SE) peak amplitude of pelvic and gesture hip, knee, and ankle angular displacement, and end segment (finger and toe) resultant displacement, within each phase of movement (passé, arabesque, return) were calculated. Resultant peak displacement of the toe and finger were normalized to lower and upper extremity length, respectively. To examine differences in the transfer of weight from bipedal to unipedal stance, pelvic translation amplitude in the frontal plane was determined.

As a measure of proximal movement consistency, within subject pelvic coefficients of variation (CV: SD/mean x 100) were determined for each plane in each movement phase (passé, arabesque, and return). Furthermore, as a measure of static balance control during arabesque hold, CV of pelvis and gesture end-segment (toe and finger) displacements were calculated.

Intra-limb temporal coordination of the gesture hip, knee, and toe was determined by difference scores of peak velocity time, time-normalized as a percentage of total movement time. Inter-limb coordination was determined by time-normalized difference scores of peak velocity time of the gesture toe and finger. In addition, time-series cross correlations were examined to determine the relationship between joints or body segments. High correlation indicated strong coupling, and low correlation indicated more independent control.

Separate between-group ANOVA comparisons were conducted for each selected parameter. Post-hoc Bonferroni group comparisons were conducted when relevant. Statistical significance was set at the $p < 0.05$ level for all tests.

Results

General Movement Organization

To determine whether the general movement timing and shape described above was similar between groups, gesture hip, knee, ankle angular and toe resultant displacement trajectories were compared. Movement onset and termination sequencing order was similar for all groups; e.g., a proximal to distal order at trial onset and a distal to proximal order at cessation in all cases (Fig. 2). Phase duration was also similar for all groups.

As described earlier, there were four discrete phases to the arabesque sequence: movement from first position to passé (passé), from passé to arabesque (arabesque), a hold in arabesque (arabesque hold), and return from arabesque to first position (return). A representative displacement trace of an EXP subject is shown in Fig. 3. At movement onset from first position to passé, pelvic tilt (T_0) preceded gesture leg movement. Angular displacement of the knee (T_1) was followed by onset of the hip (T_2), ankle (T_3), and resultant displacement of the toe (T_4). During the passé phase the hip and knee flexed as the ankle plantar flexed. In the arabesque phase, the ankle remained plantar flexed as the hip and knee extended. There were no changes in angular displacement amplitudes during the arabesque hold followed by return to first position at the conclusion of the return phase. Movement termination generally displayed a distal to proximal sequencing order: toe (T_5), ankle (T_6), knee (T_7), hip (T_8), followed by the pelvis (T_9).

Mean peak angular displacement of the gesture limb hip (flexion 60° ± 2°), knee (flexion 141° ± 3°), and ankle (plantar flexion 53° ± 2°) during the passé phase, and hip (extension 9° ± 2°) and knee (flexion 11° ± 2°) during the arabesque phase, was similar for the three groups. During the passé phase, all subjects averaged 14° ± 1° of pelvic obliquity (side bending toward the stance limb), -3° ± 1° of posterior pelvic tilt, and 3° ± 1° of transverse rotation toward the gesture limb. During the arabesque phase, subjects demonstrated an average of 35° ± 2° of pelvic obliquity toward the stance limb, 32° ± 1° of anterior pelvic tilt and 44° ± 2° of transverse rotation toward the gesture limb (Fig. 4). Pelvic obliquity and tilt displacements were similar between groups during each phase of movement. However, groups differed in

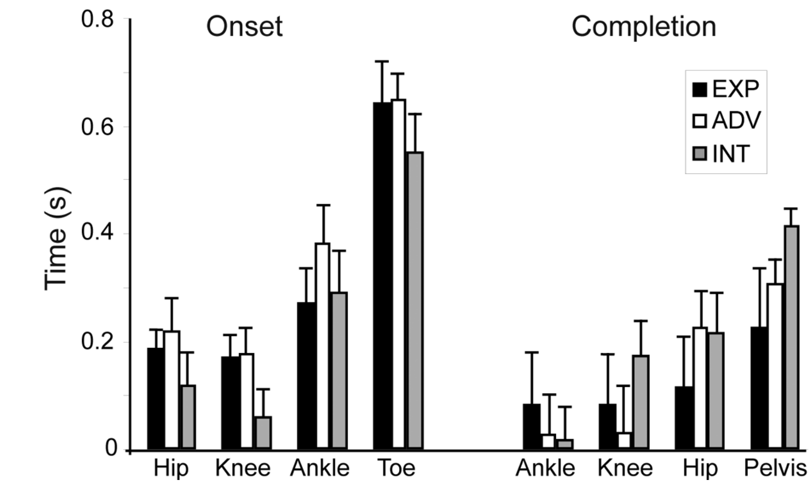

Figure 2 Mean (± SE) onset and completion times of each pelvic or limb segment relative to the segment that began moving first of Expert (black), Advanced (white), and Intermediate (gray) groups. At movement onset, displacement was determined relative to the pelvis. At movement completion, displacement was determined relative to the gesture toe.

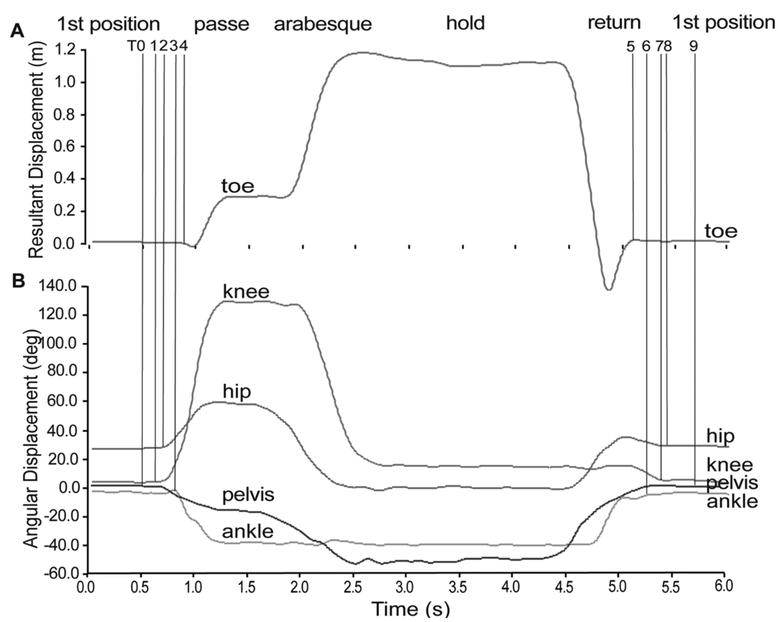

Figure 3 Arabesque movement profile of a representative trial of one expert dancer. All traces are aligned to the temporal (x) axis. Movement phases: first position, passé, arabesque, arabesque hold, return, first position are indicated at the top. **A**, Resultant displacement trajectory of the gesture toe. **B**, Sagittal plane angular displacement trajectory of the pelvis and gesture hip, knee, and ankle for the same trial of this subject.

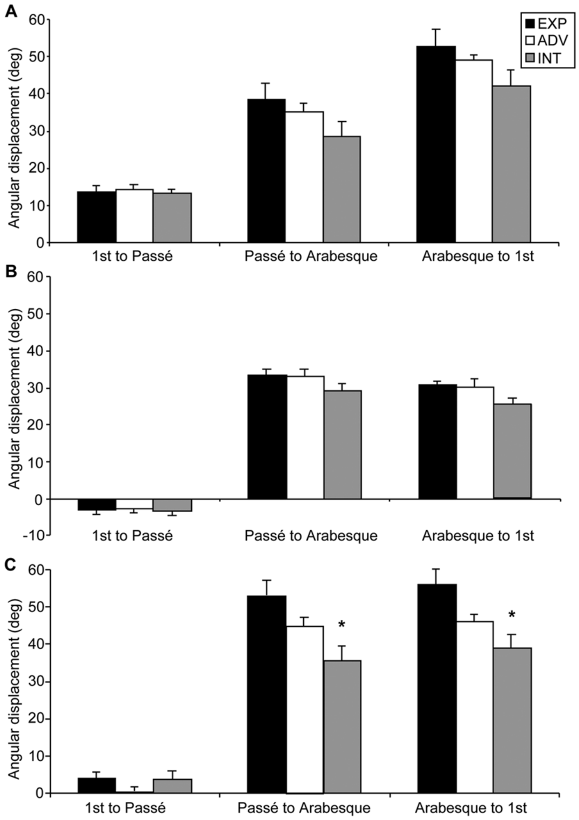

Figure 4 Mean (± SE) pelvic angular displacement of Expert (black), Advanced (white), and Intermediate (gray) groups. **A**, pelvic obliquity (side bending), **B**, pelvic tilt (flexion is +, extension is -), and **C**, pelvic transverse rotation. Note: Pelvic motion from *Arabesque to First Position* was in the opposite direction of *Passé to Arabesque* to return to the starting position. Therefore, net motion from initial first position to return to first position was approximately zero in each plane of movement. Bars with * denote significant differences between groups ($p < 0.05$).

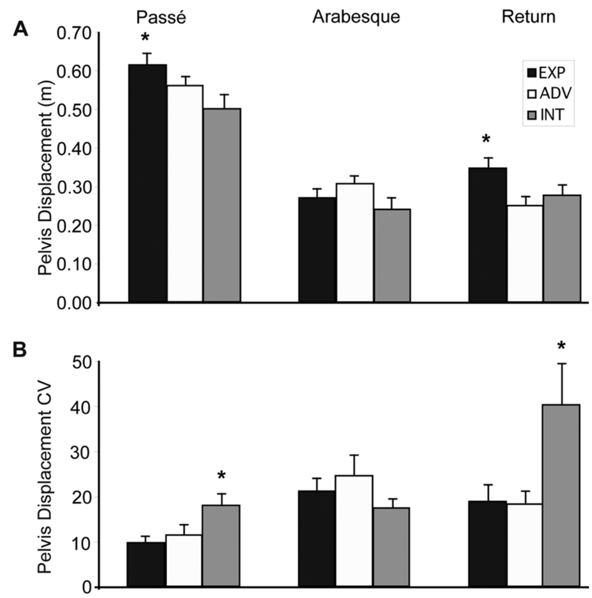

Figure 5 **A**, Frontal plane mean (± SE) pelvic translation (m), normalized to pelvic width, during movement in the passé, arabesque, and return phases of Expert (black), Advanced (white), and Intermediate (gray) groups. **B**, Mean (± SE) coefficient of variability (CV) of pelvis frontal plane displacement of the Expert (black), Advanced (white), and Intermediate (gray) groups. Bars with * denote significant differences between groups ($p < 0.05$).

pelvic transverse rotation during the arabesque phase [$F(2,24) = 6.00$, $p < 0.01$; post hoc EXP vs. INT $p < 0.01$], and return phase [$F(2,24) = 5.29$, $p < 0.05$; post hoc EXP vs. INT $p < 0.01$]. INTs performed less pelvic transverse rotation (35° ± 4°) than either ADV (45° ± 4°) or EXP (53° ± 4°) during the arabesque phase, as well as during the return phase (INT 39° ± 4°, ADV 46° ± 4°, EXP 56° ± 4°). In summary, all measures of displacement were similar between groups except pelvis transverse rotation displacement during the arabesque and return phases.

Dynamic Postural Control

To examine postural control during weight shift, pelvic translation displacement in the frontal plane was determined. Differences were found in both magnitude and consistency of pelvic translation. Group differences in mean peak displacement of pelvic translation occurred during the passé [$F(2,24) = 3.73$, $p < 0.05$; post hoc EXP vs. INT, $p < 0.05$] and, logically, return phase [$F(2,24) = 3.82$, $p < 0.05$ post hoc EXP vs. INT, $p < 0.05$] (Fig 5A). Specifically, EXP (passé 0.62 ± 0.03 m and return 0.35 ± 0.03 m) translated farther than ADV (passé 0.56 ± 0.03 m and return 0.25 ± 0.03 m) or INT dancers (passé 0.50 ± 0.03 m and return 0.28 ± 0.03 m). In addition, pelvic translation variability (CV) differed between groups during both the passé [$F(2,24) = 4.07$, $p < 0.05$; post hoc EXP vs. INT $p < 0.05$] and return phases [$F(2,24) = 4.40$, $p < 0.05$; post hoc ADV vs. INT $p < 0.05$] (Fig 5B). Intermediate dancers were more variable than either ADV or EXP dancers.

Static Postural Control

As a measure of static balance control during the arabesque hold phase, variability (CV) of pelvic displacement and resultant displacement of the gesture end-markers (toe and finger) was examined (Fig. 6). Mean variability (CV) of the pelvis differed between groups in each axis of rotation [x-axis, or pelvic obliquity: $F(2,24) = 7.81$, $p < 0.01$; post hoc EXP and ADV vs. INT $p < 0.01$], [y-axis, or pelvic anterior tilt: $F(2,24) = 27.41$, $p < 0.01$; post hoc EXP and ADV vs. INT $p < 0.01$], and [z-axis, or pelvic transverse rotation $F(2,24) = 15.64$, $p < 0.01$;

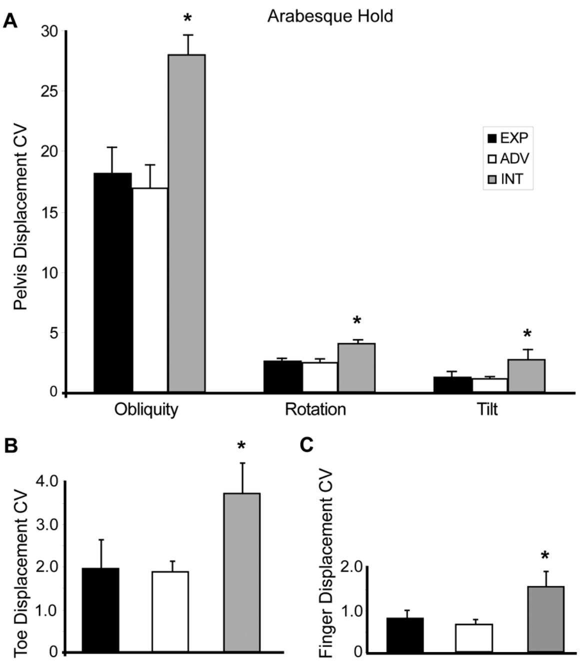

Figure 6 Mean (± SE) coefficient of variability (CV) of the pelvis, toe, and finger during the arabesque hold phase for Expert (black), Advanced (white), and Intermediate (gray) groups. **A**, Pelvic obliquity (side bending), pelvic transverse rotation, and pelvic tilt (flexion-extension); **B**, Toe resultant displacement; and **C**, Finger resultant displacement. Bars with * denote significant differences between groups (p < 0.05).

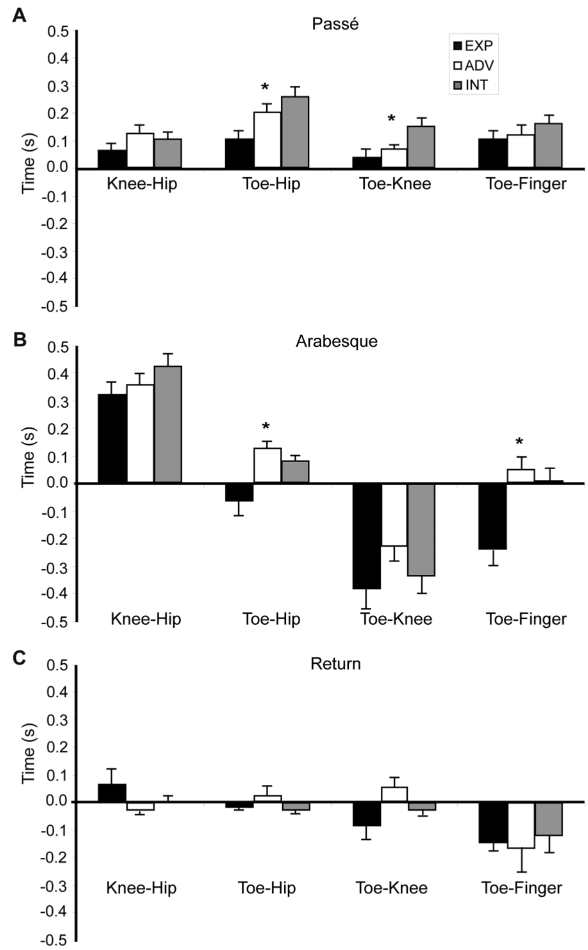

Figure 7 Mean (± SE) difference scores of the timing of peak velocity of the gesture hip and knee angular velocity and toe and finger resultant velocity of Expert (black), Advanced (white), and Intermediate (gray) groups. When the histogram is a positive value, the second joint listed peaked first. When the histogram is negative, the joint listed first preceded the second joint. Difference scores are seen for the **A**, Passé, **B**, Arabesque, and **C**, Return phases. Bars with * denote significant differences between groups (p < 0.05).

post hoc EXP vs. INT and ADV $p < 0.01$] (Fig. 6A). Mean variability (CV) of the toe [$F(2,24) = 5.37$; $p < 0.01$; post hoc EXP and ADV vs. INT $p < 0.05$] (Fig. 6B) and finger [$F(2,24) = 4.18$; $p < 0.05$; post hoc ADV vs. INT $p < 0.05$] (Fig. 6C) also differed. INT dancers displayed greater variability during the static balance than ADV or EXP dancers.

Intra-limb Coordination

Intra-limb segmental coordination of the gesture hip, knee, and toe was measured by difference scores in peak velocity timing (peak angular velocity of the hip and knee, and peak resultant velocity of the toe: Fig. 7). Segmental coordination differed between groups in both the passé [toe-hip $F(2,24) = 5.48$, $p < 0.01$; post hoc EXP vs. INT $p< 0.01$; toe-knee $F(2,24) = 5.14$, $p < 0.01$; post hoc EXP vs. INT $p < 0.01$] (Fig. 7A) and arabesque phases [toe-hip $F(2,24) = 8.23$, $p < 0.01$; post hoc EXP vs. INT and ADV $p < 0.05$] (Fig. 7B). In the passé phase, toe-hip and toe-knee peak velocity timing were more tightly coupled in EXP and ADV dancers compared to INT dancers. In the arabesque phase, timing of peak velocity of the toe preceded that of the hip in the EXP group. This was the opposite of that seen in ADV and INT dancers, demonstrating a different inter-segmental coordination pattern. During the return phase (Fig. 7C), there were no differences between groups. There were no differences between groups in CV of these analyses.

Inter-limb End-segment Coordination

Inter-limb coordination of the gesture toe and finger were also measured by difference scores in peak (resultant) velocity timing (Fig. 7). Differences were again found during the arabesque phase [$F(2,24) = 8.81$, $p < 0.01$; post hoc EXP vs. INT and

ADV $p < 0.01$] (Fig. 7B). The timing of peak velocity of the toe preceded that of the finger in the EXP group. This was the opposite of that seen in ADV and INT dancers, demonstrating a different inter-limb coordination pattern.

In time-series cross correlation analysis, both ADV and INT dancers displayed tighter temporal coupling of the gesture finger and toe compared to EXP dancers (correlations EXP $r = 0.80$; ADV $r = 0.88$; INT $r = 0.89$) [$F(2,24) = 149.447$, $p < 0.01$].

Discussion

The purpose of this study was to determine how skill level affects multijoint posture and limb coordination in a sequential dance task. Subjects displayed similar movement shape, general organization and timing, and spatial orientation to the global (external) and body (internal) reference frames. This was demonstrated by 1. similar trunk-limb movement onset and termination sequencing and phase duration and 2. gesture limb peak resultant and angular displacements, regardless of training level. Differences between groups lay in postural and balance control and intra- and inter-limb coordination. These differences were most apparent during the arabesque phase. Control of the pelvis appears to be a key area that requires prolonged practice to master.

Attainment of Movement Organization and Shape

In general, early learning of a task first requires mapping out the movement necessary to complete it. This involves exploration of both movement shape and timing. Current motor learning theory suggests that explicit learning, a process available to consciousness that peaks with relative rapidity, is concerned with this mapping out of movement shape and form.[21] Therefore, it was expected that the subjects in the current study, all of whom were at least intermediate level dancers, would demonstrate similar spatial (shape) and temporal organization within each movement phase. This was indeed the case with regard to movement sequencing and amplitude of normalized resultant and angular displacements. Furthermore, the proximal to distal sequencing seen at movement onset and the reverse at movement termination resembles the sequencing described in many sports movements such as kicking and throwing,[24] as well as in the passé of elite dancers.[25]

General timing and phase duration of the pelvic and limb segments were similar and consistent between groups. This was anticipated due to the temporal constraints of the metronome. Dance training involves strict adherence to musical tempo.

Both amplitude and consistency of peak angular and resultant velocity of the gesture leg were also similar between groups. The only difference between groups in movement amplitude was pelvic transverse rotation angular displacement. Experts displayed greater pelvic transverse rotation during the arabesque and return phases. Similarly, in another study skilled dancers displayed greater pelvic motion in all planes during performance of the grand rond de jambe en l'air than did less skilled dancers.[26] Skilled baseball pitchers display increased thoracic and pelvic transverse rotation, which may contribute to throwing at higher velocities compared to less skilled pitchers.[27] The arabesque sequence had strict temporal constraints; therefore, increased pelvic rotation likely reflected a different strategy. It may be that the greater pelvic transverse rotation afforded a more stable pelvis for the arabesque hold phase; that is, rotation of the pelvis with counter-rotation of the trunk above to face forward and counter-rotation of the hip below to maintain turnout may create a locking of the trunk-pelvis-stance hip to create improved stability.

Intermediate dancers may have limited pelvic rotation in order to control the multiple degrees of freedom present during the more complex arabesque phase. While the entire développé arabesque sequence is practiced in every ballet class, the passé is practiced approximately four to five times more frequently (the passé is used in turning, as part of the développé sequence to the front and side, and so forth). In addition, the passé shape maintains a vertical orientation, while the arabesque phase involves a change in trunk orientation with simultaneous movement of the gesture leg and arm, thus requiring control of additional degrees of freedom. An alternative explanation for why there was greater pelvic transverse rotation with increased skill involves style of ballet training. Porte de bras placement and trunk and pelvic shape in the arabesque may vary with teacher. However, all EXP dancers were trained in the same school as dancers in the ADV and INT groups and take technique class there regularly.

Differences in Dynamic and Static Postural Control

Despite similarities in general movement shape, dynamic postural control differed with skill level as manifested in different displacement of the pelvis. Experts translated their pelvis farther during the weight shift from bipedal to the stance limb during the initial passé phase, and the reverse during the final return phase. The finding of greater amplitude of pelvic translation with increasing skill level diverges from previous comparisons of dancers and naïve subjects,[5,28] as well as gymnasts and untrained controls.[5,18] Mouchnino and colleagues[5] reported that frontal plane center of gravity excursion was less in dancers compared to controls during performance of a leg abduction movement. However, task constraints of timing ("as quickly as possible") and limb amplitude and direction (to 45° abduction) may have dictated a minimization strategy of center of gravity displacement. In the Mouchnino and colleagues study, frontal plane center of gravity excursion was counterbalanced by the abducted gesture limb, thus minimizing the necessary excursion.

In contrast, to accomplish the passé, dancers shifted to a one-legged stance while bringing the gesture toe to the knee of the stance limb (Fig.

1B). This required a greater excursion of pelvic translation to bring the pelvis over the stance foot in order to maintain equilibrium relative to leg abduction. Trained dancers and gymnasts have been shown to displace their center of gravity more efficiently, with a shorter adjustment duration than naïve subjects.[5,18,28] In this study, the greater pelvic excursion seen in EXP dancers may reflect both movement efficiency and preparation for the next sequence to follow.

The translation strategy observed elsewhere in skilled dancers during leg abduction but not in naïve subjects[5] was present during the passé phase at all levels of skill in this study. In previous studies, dancers demonstrated less variability of pelvic displacement than naïve subjects with limb movements in all directions.[5,28] Here, dancers with increased skill (EXP and ADV) exhibited less variability of pelvic translation than INTs, suggesting that development of consistent control of the pelvis takes prolonged practice.

The arabesque hold phase required integration of postural control with gesture (focal) upper and lower limbs in a complex balance task. Less variability was anticipated with increased skill (CV of pelvic angular displacement and gesture end-segment toe and finger resultant displacement). Customarily, the arms may be used to enhance the height of a jump or stabilize a balance. In this case, increased variability was found throughout the pelvis and limbs with less skill during the static balance. Further studies investigating ground reaction forces and center of pressure measures may provide insight into static balance control in a complex task such as this.

Intermediate dancers displayed relative instability during static balance control as demonstrated by large variability (CV) of the pelvis in each plane of motion, as well as variability of the toe and finger. The balance control of EXP and ADV dancers was relatively stable and similar for the two groups. More stable balance control due to increased skill has been previously documented in dancers[5,29] and gymnasts.[30]

Interestingly, CV values of pelvic obliquity (frontal plane) were more than ten times that of pelvic tilt (sagittal plane), and six to seven times those of pelvic transverse rotation for each of the groups, suggesting that frontal plane pelvic motion was most difficult to control with consistency (Fig. 6). Postural control in the frontal plane has received less attention in the literature compared to the sagittal plane.[31-33] Within subject variability has been reported to be highest in the frontal and transverse planes for both kinematic and kinetic human gait data, compared to that of the sagittal plane.[29] Control of postural stability in the frontal plane was found to be the most important contributor to kicking performance in soccer players.[34] Dynamic and static balance control in the frontal plane may be challenging due to the narrowness of the foot width and the relationship of foot position relative to the center of mass.

In the arabesque task, the turned out (externally rotated) position of the lower limbs should afford additional stability over parallel stance, as the Y-ligaments of the hip are taut and the hip joint is more close-packed. However, it is primarily the muscles of the stance hip that must stabilize the trunk and gesture limbs. Variability (CV) at the pelvis was much greater than that of the gesture limb end-segments (toe and finger). The pelvis, as the common intersection of the lower limb, trunk, and upper extremity, appears to be the key point of both gesture and postural control. Pelvic variability may be partly due to insufficient stance hip strength or difficulty in controlling the interactional torques of the lower limb. The higher variability found in the INT group may also be interpreted as a reflection of exploratory behavior to refine an existing control pattern or reorganize into a new pattern or "coordinative structure."[35] Further research is warranted to investigate differences in interactional torques during performance of complex dance movements in dancers of differing skill levels.

The greater variability seen at the gesture limb end-segments in the INT group during the arabesque hold was likely a reflection of large variation in postural control at the pelvis. This instability was transmitted along the kinetic chain to the end-segments. However, variability at the toe was more than twice that at the finger in all groups. There are several possible explanations for this. Reaching arm movements are over-practiced in comparison to reaching leg movements and are generally performed within the field of vision. Although the arabesque requires a large change in trunk position (extreme extension of the spine), the shoulder girdle and head-neck remain oriented to the vertical. Control of the gesture lower limb is a much greater motor challenge. The pelvis is no longer in a familiar vertical orientation, and the lower limb is held horizontally out of the field of vision while requiring modulation of a larger inertial load.

Differences in Intra-limb and Inter-limb Coordination

Acquisition of complex movement skill initially involves reducing kinematic degrees of freedom and later releasing them to modulate movement effectiveness and increase efficiency.[4,11,36] The emergence of altered coordination patterns and decreased or altered joint coupling is hypothesized to be part of the learning process as the performer modulates force dynamics to perform the task more effectively.[37] There were no differences between groups in lower limb segmental peak velocity coordination in the return phase, suggesting that all dancers had solved the simpler organization strategy of lowering the limb to return to first position.

Segmental control differed between groups in the passé phase, with the toe-hip and toe-knee temporally coupled more tightly in the EXP group. This is consistent with the greater pelvis translation found in the EXP dancers in the weight shift to single limb stance.

Segmental coordination also differed between groups in the more complex arabesque phase. Peak velocity timing of the toe-hip and toe-finger was coupled in a different order in EXP dancers. There were no differences between ADV and INT groups, suggesting that reorganization of intra- and inter-segmental coupling requires greater skill. The coordination differences at the toe-hip and toe-finger due to increased expertise resemble the proximal-distal directional trends of skill acquisition seen in tasks such as dart throwing,[4] volleyball,[10] and badminton.[38]

The time series cross correlation indicated that, overall, EXPs were least tightly constrained in performance of this sequential movement. The increased temporal constraints of inter-joint coordination found in ADV and INT dancers may be explained by the increased variability measured at the pelvis, toe, and finger. While this movement strategy was efficacious in attaining the positions of the task, it was not necessarily the most efficient option. EXPs, on the other hand, had more independent segmental control, allowing for decreased variability throughout the task.

Coordination between multiple segments of the gestural or focal limb produces one level of complexity. Coordination of the multi-segmental limb with an extreme change in postural orientation adds a second level. A third level entails coordination of one limb with another (upper extremity with lower extremity) of disparate proportions and mass. In cross correlations, ADV and INT dancers displayed tighter temporal coupling of the gesture finger and toe compared to EXP dancers. That tighter coupling was retained even in the ADV group suggests that mastery of each of the levels of control—intra-limb posture and inter-limb coordination—continues to be modulated throughout practice.

Conclusion

Massion[39,40] suggested that movement can be divided into two main types of control: maintaining a reference value against an internal or external disturbance and the displacement of one or more segments along a trajectory to achieve some goal. These two control components differentiate a moving segment or limb as the *focal* (i.e., gestural) chain from a *postural* chain, which is interposed between the focal limb and base of support or is part of the postural limb.[41] The arabesque sequence can be viewed as a complex dynamic postural task involving weight shift to unipedal stance, change in trunk orientation, and static balance. However, this sequence is also a reaching task with accuracy constraints. The toe of the gesture leg is aiming for a point on the stance knee in the passé phase. During the arabesque phase, the gesture upper and lower limbs are aiming for alignment in the sagittal plane while also achieving a posture parallel to the ground. Differences due to skill level in both postural and gestural variables suggest modification is ongoing in both focal and postural control variables.

Skilled performance of the arabesque sequence requires mastery of both postural control and segmental coordination to regulate the inertial forces generated by large limb and trunk accelerations. Dance students frequently focus their attention on maximizing displacement of the gesture leg (e.g., how high can they lift it). However, successful mastery of pelvic control as well as segmental timing appears to be a key area that differentiates expert from student dancers. Prioritization cannot be given to either control system (postural versus focal and gestural), as this study demonstrates that coordination of both posture and gesture limbs continues to be modified by on-going practice.

Kinematic analysis of this complex movement provides insight into the underlying control of movement dynamics. Dynamic analyses are required to provide further understanding of changes in the coordination of passive and active forces due to skill acquisition. The arabesque requires mastery of large changes in trunk and limb orientation with respect to the vertical and involves control of a complex combination of degrees of freedom. Analysis of intra-limb segmental and inter-limb coordination of velocity timing as well as cross correlations affords us some understanding of the prolonged period during which reorganization continues to occur.

Comparisons of groups of varying skill levels are useful for describing the development of expertise. Group differences in posture and balance control, as well as intra- and inter-limb coordination, demonstrate how the reorganization and modulation of control continues over years of practice.[37,42,43] Use of the naïve-expert paradigm fails to provide an understanding of the timeline of reorganization, coordination, and modification occurring in complex limb and postural integration as attempted in this study. However, analysis of skill acquisition over prolonged periods of training does provide a window into how the central nervous system continues to grapple with coordination and control of multiple degrees of freedom in truly complex movements.

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