Biomechanical Research in Dance: A Literature Review

Donna Krasnow, MS, M. Virginia Wilmerding, PhD, Shane Stecyk, PhD, ATC, CSCS, Matthew Wyon, PhD, and Yiannis Koutedakis, PhD

The authors reviewed the literature, published from 1970 through December 2009, on biomechanical research in dance. To identify articles, the authors used search engines, including PubMed and Web of Science, five previous review articles, the *Dance Medicine and Science Bibliography*, and reference lists of theses, dissertations, and articles being reviewed. Any dance research articles (English language) involving the use of electromyography (EMG), forceplates, motion analysis using photography, cinematography or videography, and/or physics analysis were included. A total of 89 papers, theses/dissertations, and abstracts were identified and reviewed, grouped by the movement concept or specialized movements being studied: alignment (n = 8), *plié* (8), *relevé* (8), *passé* (3), *degagé* (3), *développé* (7), *rond de jambe* (3), *grand battement* (4), arm movements (1), forward stepping (3), turns (6), elevation work (28), falls (1), and dance-specific motor strategies (6). Several recurring themes emerged from these studies: that elite dancers demonstrate different and superior motor strategies than novices or nondancers; that dancers perform differently when using a barre as opposed to without a barre, both in terms of muscle activation patterns and weight shift strategies; that while skilled dancers tend to be more consistent across multiple trials of a task, considerable variability is seen among participants, even when matched for background, years of training, body type, and other variables; and that dance teachers recommend methods of achieving movement skills that are inconsistent with optimal biomechanical function, as well as inconsistent with strategies employed by elite dancers. Measurement tools and the efficacy of study methodologies are also discussed. *Med Probl Perform Art* 2011; 26(1):3–23.

Biomechanics is "the scientific discipline that studies the mechanical principles of human movement and provides information on muscular function and its characteristics."[1(p73)] Dance inquiry involving the principles and techniques of biomechanics dates back to the early 1960s with the work of Kneeland.[2] However, it was the pioneering researchers of the 1970s who first introduced the measurement tools and research methodology that were the forerunners of the current equipment and approaches used today.

They began to question how dancers performed dance movements, using science to examine how these movements were actually executed. Graduate students at the University of Oregon and Texas Woman's University[3–10] and university researchers[11–15] conducted innovative studies with rudimentary equipment and technology that would, by today's standards, be considered tedious and cumbersome. And yet these researchers made landmark discoveries in the field of dance biomechanics and inspired generations of dance scientists to further the pursuit.

It is of interest to ask what questions these early researchers were examining, and how they might compare to the current literature in dance science. Further, we can assess the tools available to the early researchers, and how these tools compare to the electromyography, force measurement, and video motion analysis apparatus available to today's researchers. Finally, a better understanding of how to best use biomechanical equipment in the laboratory setting might be gained by examining how dance researchers are using these evolving instruments compared to the studies in the past.

In the decades that followed these early studies, researchers began to have access to more sophisticated technology. Electromyography became capable of increased numbers of channels, allowing more muscles to be investigated simultaneously. Motion analysis evolved from cinematography and hand drawn graphs, to multiple cameras with computerized data collection and graphing. At the same time, researchers began examining dance performance in laboratory settings internationally. Some were interested in establishing baselines of performance, i.e., establishing normative profiles of elite dancers. Topics of interest included alignment,[16] *plié*,[6,17–20] *relevé*,[21–24] *passé*,[25] *degage*,[26] *développé*,[27] *rond de jambe*,[28] *grand battement*,[15,29,30] arm movements,[31] turns,[12,32,33] elevation work,[5,14,34–40] and falls.[7]

Other researchers were interested in comparing elite dancers with novice dancers or nondancers[28,41–50] or with athletes in other professions,[51] or comparing male and female dancers.[52,53] Other researchers designed studies that questioned traditional teaching methodologies or proposed new insights or approaches to dance training and motor strategies.[9,10,37,54–67] And some of

Ms. Krasnow is Professor, Department of Dance, Faculty of Fine Arts, York University, Toronto, Ontario, Canada, and Lecturer, Department of Kinesiology, California State University, Northridge, California, USA; Dr. Wilmerding is Adjunct Professor in the Department of Dance and Assistant Research Professor in the Department of Health, Exercise & Sports Sciences, University of New Mexico, Albuquerque, New Mexico, USA; Dr. Stecyk is Associate Professor and Director of the Athletic Training Education Program, Department of Kinesiology, California State University, Northridge, California, USA; Dr. Wyon and Dr. Koutedakis are with the Research Centre for Sport, Exercise and Performance, University of Wolverhampton, Walsall, UK; Dr. Wyon is also with the Jerwood Centre for the Prevention and Treatment of Dance Injuries, Birmingham, UK, and Dr. Koutedakis is also with the Department of Exercise Sciences, University of Thessaly, Trikala, Greece.

Address correspondence to: Donna Krasnow, MS, Professor, Department of Dance, Faculty of Fine Arts, Accolade Building East 313, York University, 4700 Keele Street, Toronto, ON M3J 1P3, Canada. Tel 416-736-5137 x22130. DKrasnow1@aol.com.

the researchers focused on anatomical or biomechanical factors that may be precursors or correlates to injury.[39,66,68–80]

As research capabilities progress, the capacity to see and understand movement with greater clarity emerges. What was once "known" with the naked eye is questioned, examined, and reformulated. This process, however, raises more questions. Researchers ask if differences between elite and novice dancers are due to training practices or innate differences. They sometimes assume that the profiles created by observing elite dancers yield the optimal method of achieving a particular skill, but this may or may not be the case. Methods of analysis are examined, and researchers try to determine if they can learn more useful information by looking at a few participants extensively, or looking at larger numbers and comparing group means. The focus of this article is to review the articles in the dance literature involving biomechanical equipment and to examine the efficacy of current methodologies.

REVIEW METHODOLOGY

To find relevant articles for the current review, the authors used search engines, including PubMed and Web of Science, five previous review articles,[81–85] the *Dance Medicine and Science Bibliography*,[86] and the reference lists of theses, dissertations, and articles being reviewed. Any dance research articles involving the use of electromyography (EMG), forceplates, motion analysis using cinematography or videography, and/or physics analysis have been included. In order to ensure the broadest scope in looking at the current literature, no exclusion criteria were employed, other than restricting the review to English-language articles. Since many research studies in dance are presented at conferences and represented by abstracts or brief summaries, these short descriptions have also been reviewed, despite lacking some of the necessary information for a complete understanding of the work. Finally, a small number of theoretical articles have been included due to their perspective on biomechanical research and methods of analysis.

Articles were grouped based on the movement concept or specialized movements being studied: alignment, *plié, relevé, passé, degagé, développé, rond de jambe, grand battement*, arm movements, forward stepping, turns, elevation work, falls, and dance-specific motor strategies. Although there is some overlap in the categories, this method of grouping the articles provided the most provocative insights. Within each group, articles are discussed chronologically, to emphasize the development of the technology over time. This review concludes with an overview of potential limitations in research methodologies to date and questions that arise from the body of research studies currently available.

CATEGORIES OF ARTICLES BASED ON DANCE MOVEMENT

Alignment

Although researchers and educators have varying definitions of alignment, the most common is based on the arrangement of the body segments and skeletal structure in a vertical column with respect to the line of gravity.

One of the early research studies investigating alignment was a master's thesis by Bannister (1977),[3] which examined the interrelationships of pelvic angle, lumbar angle, hip mobility, and the correlation of alignment to low back pain. Participants were 8 male and 55 female university dance students. They were photographed from front and side views, next to a plumb line suspended from the ceiling. Measures of flexibility were taken for hip flexion and abduction in a seated position, and pain was assessed by questionnaire. Analysis consisted of *t*-tests and Pearson product moment coefficient of correlation. Bannister concluded that the four variables (lumbar angle, pelvic angle, and flexibility in hip flexion and abduction) do not predict low back pain and that posture, flexibility, and pain are independent.

Nichols (1979)[13] examined deviations in verticality in the upper spine, lower spine, and total spine and what effects these deviations had on how dancers executed the *grand plié*. Additionally, she considered the influence of the use of the ballet barre and dance experience. There were a total of 28 participants in the study, divided into four equal groups: 21 female undergraduate students with no dance experience divided into three groups based on the ratio of upper spine length to total spine length, and 7 additional advanced ballet students. Coincidentally, the ballet dancers all had spine ratios similar to the middle group of nondancers. Participants were filmed from a side view with a Vanguard Motion Analyzer, with five white circles placed on the body as landmarks. They executed five *grand pliés* with and without the barre. Analysis was a $4 \times 2 \times 5$ ANOVA with variables defined by various spinal deviations from vertical as the dependent variable, and experience levels, barre/no barre, and various positions for the *plié* as the independent variables. Results indicated that spinal ratio had no effect upon alignment deviations. Verticality of the spine was not related to experience, but experience did influence consistency in the task. Further, lack of flexibility was also an issue in consistency of movement. Finally, at the deepest moment of the *plié*, there were reductions in alignment deviations when using the barre but not without the barre, even in the experienced dancers.

In her master's thesis, Minton (1981)[9] examined the effects of verbal-visual cues on dancers' alignment and compared varying approaches to cuing, based on the work of Lulu Sweigard. Data were collected with a 35-mm camera for still photographs and a 16-mm motion picture camera. Still shots were done in standing and walking, while filming was done in the walking condition only. Participants were 60 female dancers, 20 from each of three beginner modern dance classes. Participants were selected using criteria establishing the students showing the greatest need for improvement. Filming took place at 3 weeks into the term, and again 6 weeks later. Three different approaches to cuing were randomly assigned to the three groups: (1) subconscious, anatomically based images; (2) subconscious, pictorial images; and (3) conscious attempts to move body segments. Alignment of each participant was determined by adding measured deviations from the plumb line determined by several body landmarks. Tracings were made on both the still photographs and motion films, and deviations from the plumb line and center of gravity were determined. A one-way analysis of covariance was done for pre- and post-test comparisons.

Results indicated that some improvement occurred from pre- to post-testing, but the changes were not significant and were different for each group. In some body areas, alignment got worse. The researchers could not state if improvements were due to the interventions or to regular dance class. Regarding the three interventions, subconscious, anatomically based images were not significantly different than subconscious, pictorial images, and neither of those interventions was better than conscious attempts to move body segments. These results were found for both the still photographs and films.

Woodhull-McNeal, Clarkson, James, Watkins, and Barrett (1990)[16] analyzed the alignment of 13 female college dancers in four common dance positions (parallel first, and turned-out first, third, and fifth), by photographing the dancers from the side and then measuring distances between bony landmarks including ankle, knee, hip joints, pelvis, shoulder, and ear. The measure of best alignment was represented by values coming closest to being in a straight line, i.e., closest to zero. Analysis was a repeated measures ANOVA with post hoc tests for differences. Results of their study indicated that alignment in turned-out first position was significantly closer to a straight line through the plumb line represented by the bony landmarks than the other three dance positions. Additionally, anterior pelvic tilt was significantly greater in fifth position than the other three positions. This suggests that alignment is variable by condition in individual participants.

Krasnow, Chatfield, Barr, Jensen, and Dufek (1997)[58] conducted an intervention study, measuring both static and dynamic alignment using the Peak 5 Clinical and Research Video System. Data were collected with a single camera, using eight reflective markers along the right side of the body. A plumb line was suspended from the ceiling in camera view to ensure vertical accuracy. The participants were 20 university dance students, divided into four groups: conditioning only, imagery only, conditioning with imagery, and controls. Participants performed six trials of the *grand plié* in first position turned out, three from static stance and self-paced, and three with an off-center torso movement preceding the *plié* with music. Participants were pre- and post-tested, with 8 weeks of intervention. Analysis consisted of 4 × 2 × 2 (group by time by condition) ANOVA.

All participants improved from pre- to post-testing, which is not surprising given that all were participating in ongoing dance training. Additionally, participants in all four groups demonstrated significantly larger scores (markers further from the plumb line) in Condition 2, the condition in which the off-center torso movement preceded the *plié*. When looking at different moments during the *plié*, it was further discovered that the group who did conditioning with imagery showed the greatest improvement from pre- to post-testing at the moment between the end of the off-center torso movement and the return to vertical to start the *grand plié*. This result indicates that they were able to find better alignment more quickly in a dynamic situation than the other groups after the intervention. In addition to supporting a combined use of conditioning and imagery for improving alignment, the researchers also concluded that it is essential to study alignment in dynamic rather than static conditions.

Gamboian, Chatfield, Woollacott, Barr, and Klug (1999)[57] conducted an intervention study looking at the effects of both dance training and somatic training on alignment. Specifically, the researchers investigated pelvic tilt and lumbar lordosis in two studies, both using the same methodology. Six reflective markers were placed on the body and on wands attached to the body, to establish changes in pelvic and lumbar angles. Data were collected with one camera, using the Peak 5 Performance Analysis System, filmed from a lateral view on three consecutive pre-test days and three consecutive post-test days, in order to evaluate day-to-day variability. The participants performed five trials of each of three conditions: quiet stance, *plié,* and *relevé* in first position turned out, and a leg brush to forward lunge with return to stance. In study 1, three novice dance students participated in 4 weeks of dance training. A within-subjects analysis was used, and none of the participants improved post-test. All three participants demonstrated less lumbar lordosis in quiet stance than in motion. In study 2, three other dance students with more dance background participated in 4 weeks of somatic training. A within-subjects analysis was used, and participants improved in lumbar lordosis; further, the participants showing the greatest deviations in pre-testing exhibiting greatest improvement. Both studies also indicated that lumbar lordosis and pelvic tilt are independent, suggesting differing alignment strategies such as thoracolumbar hinging, which allows lumbar lordosis to diminish without any change in pelvic tilt.

Gamboian, Chatfield, and Woollacott (2000)[55] reported on further effects of somatic training on pelvic tilt and lumbar lordosis in a study with six female undergraduate recreational dancers. Data were collected with one camera, using the Peak 5 Performance Analysis System, filmed from a lateral view, with the same markers as in the previous study. Participants were pre-tested, entered the study at different points in the training (weeks 1 to 3), post-tested after the 4 weeks of somatic training, and tested 2 weeks later for retention. Participants were tested in three conditions: quiet stance, *plié,* and *relevé*, and with a torso roll preceding the *plié*. Analysis was a 6 × 3 × 3 analysis of covariance, followed by a 3 × 3 (condition by time) analysis on each participant. Overall conclusions of the study include: (1) somatic training can be effective in improving alignment and retaining improvements, (2) there is day-to-day alignment variability, (3) pelvic tilt and lumbar lordosis are independent, (4) participants use different strategies for differing conditions, and (5) individual differences can be revealed through within-subject analysis.

Wilmerding, Gurney, and Torres (2003)[66] assessed the degree and magnitude of changes in the angle of pelvic tilt in young dancers training in flamenco dance. Data were collected with a Vicon motion analysis system with multiple reflective markers on the lower extremities and pelvis. Participants were 10 girls and 6 boys between the ages of 4 and 12 years old who had trained in flamenco dance. Data were collected in the following two conditions: (1) standing barefoot and feet flat on the floor, and (2) standing barefoot with heels on a 2-inch platform, to simulate the use of the standard flamenco shoe. Analysis consisted of *t*-tests. There were no significant differences in left and right sides and no differences based on age, height, or gender. There was a significant change in the angle of plantar flexion when participants were on the platform. Variance in hip, knee, and pelvis angles did not correlate with ankle changes. Individual strategies may account for the lack of significant change in pelvic tilt, as some dancers used anterior pelvic tilt while others used posterior pelvic tilt to compensate for the elevation of the platform.

Plié

The dissertation research by Lessard (1980)[6] was conducted to determine normative mechanisms for the performance of *grand plié*, to validate the purpose of the *plié* as practiced, and to provide a rationale for adding torso movement to the *plié*. Data were collected in the frontal view and overhead view with a 16-mm Bell & Howell motion picture camera and from the sagittal view with an Actionmaster camera. Felt markers were used to denote body landmarks. Due to loss of data in the overhead view, these data were discarded. Participants were selected in three stages. Initially, 25 volunteer dance majors performed the *grand plié* twice in first position (no torso movement) for a panel of judges comprising dance professionals (condition 1). The judges selected the 12 participants who performed the most accurate *pliés;* these 12 participants then executed two additional *pliés* in each of two conditions—condition 2 added torso flexion and condition 3 added torso lateral flexion. Finally, the judges selected the top 3 participants for analysis. The data were analyzed with a Lafayette Motion Analyzer, and descriptive statistics were used to determine means, standard deviations, and maximums and minimums of joint excursions. Finally a computer program called LAMB.FOR was used to obtain velocities, moments, center of gravity, and other biomechanical measures. Results suggested the following: (1) dancer C's *plié* in condition 1 was nearly identical to dancer A's; (2) dancer C's *plié* in condition 2 was nearly identical to dancer B's; (3) all 3 participants had similar *pliés* with respect to muscle use, except condition 3 for dancer C. Lessard concluded that adding torso movement to the *plié* is sound but it increases difficulty level and should not be used with beginners.

Ferland, Gardener, and Lèbe-Néron (1983)[44] were interested in comparing dancers at different levels performing *demi pliés*, looking at EMG activity of the rectus femoris and bicep femoris. This article is a short abstract and therefore not all information is reported. Participants (total number not stated) were adult females studying classical ballet or modern dance and were divided into three groups: beginner, intermediate, and advanced. In addition to the EMG data collection, participants were filmed. While not explicitly stated, the researchers used some method to determine each participant's maximum contraction for these two muscles, making it possible to compare EMG amplitudes of trial means. The researchers concluded that advanced dancers had significantly lower biceps femoris activation at initiation of flexion and extension than the other two groups, and they had significantly lower rectus femoris activation at the end of the flexion phase than the beginners. The authors suggest that training may result in more efficient use of muscles around the hip and knee in this activity.

Woodruff (1984)[20] investigated the *grand plié* performed in first and second position at the barre. This study had one participant, an elite ballet dancer, and Woodruff acknowledged that the results could not necessarily be generalized. No details were given regarding number of trials. Data were collected using motion analysis, but there is no specific description. Analysis was a descriptive discussion of center of gravity (CoG) displacements. In first position, there was minimal CoG displacement, but in second position, there was a large CoG displacement toward the barre. There was an unexpected ankle pattern during the first position *plié*, consisting of flexion, slight extension, followed by flexion again. The highest muscular moments occurred in second, suggesting that this position requires greater strength than first position, and that second position creates greater stress on the knee.

Clippinger-Robertson, Hutton, Miller, and Nichols (1986)[71] also investigated the second position *grand plié*, using both cinematography and EMG. Fourteen participants were selected and matched according to level and type of dance studied. All were intermediate to professional ballet or modern dancers. Participants were filmed, and analysis using graphs and measurements was done at 30°, 60°, 90°, and full knee flexion. EMG electrodes were placed on vastus medialis, biceps femoris, and adductor longus. The number of *pliés* performed was not stated. Cinematography revealed that there was a trend for dancers with chondromalacia to incline the trunk forward and tilt the pelvis anteriorly, not seen in matched participants without chondromalacia. EMG data suggested that dancers with chondromalacia utilized greater muscle amplitudes overall, and in particular there was quadriceps dominance. There was no discussion of how amplitudes were compared, or if maximum contractions were determined. The researchers also noted the great individual variability in muscle use, even in matched participants, and the plasticity of the participants' motor patterns when given a variety of cues and feedback.

Trepman, Gellman, Solomon, Murthy, Micheli, and De Luca (1994)[18] examined standing posture and the *demi plié* using EMG and videotaping. Participants were five ballet and seven modern professional female dancers. Electrodes were placed on the right leg on the following muscles: lateral gastrocnemius, medial gastrocnemius, tibialis anterior, vastus lateralis, vastus medialis, gluteus maximus, hamstrings, and adductors. For the standing data collection, participants were recorded in first position three times for a 4-second period. *Pliés* were performed five times in first position over a 6-second period. Various joint angles were determined from the videotape using a goniometer. Analysis was performed for average values using *t*-tests, chi-squared test, and a two-way ANOVA for height and joint range of motion against time. In order to compare participants' EMG data and to create individual and group averages, the researchers observed peaks and valleys in the normalized EMG graphs to define minimum and maximum values. This procedure is fairly unique in the literature and an interesting variation from the use of maximum voluntary contractions (either concentric or isometric) seen in the sports literature. For standing posture, muscles were graded as having either baseline activity throughout the trial or activity above baseline.

When all dancers were considered together, EMG activity above baseline was seen most frequently in the medial gastrocnemius (greater in the ballet dancers) and tibialis anterior (greater in the modern dancers). For the *demi plié*, the ballet dancers demonstrated significantly more activity than the modern dancers in four of the eight muscles tested (lateral gastrocnemius, medial gastrocnemius, gluteus maximus, and adductors) in various phases of the *plié*. At the end of the *plié,* there was significantly more activity in the quadriceps of the ballet dancers, which the researchers suggested was due to genu recurvatum and the classical aesthetics. Additionally, there was considerable variation between individuals, regardless of training.

Trepman, Gellman, Micheli, and De Luca (1998)[19] wrote a second article on the data collected from the earlier study, looking at the *grand plié* in first position. The results supported the idea that muscle activity can be described in three categories: (1) muscle activity required for execution of the movement, (2) muscle activity differentiated based on dance idiom or form being studied, and (3) muscle activity that is individual, based on factors such as body characteristics, motor strategies, balance, and individual training. One of the striking observations in the analysis of the muscle use in the *grand plié* was that it is not simply a deepening of the *demi plié*, but rather a distinct movement using different muscles, and may therefore be essential to dance training.

Barnes, Krasnow, Tupling, and Thomas (2000)[17] investigated external longitudinal rotation (ELR) at the knee in the execution of *grand pliés* in second, third, and fourth positions. Participants were 10 professional female ballet dancers, who performed three *grand pliés* and one *demi plié* in each position. Data were collected with two video cameras and the Ariel Performance Analysis System, with multiple markers placed on seven lower leg segments. Analysis consisted of an ANOVA on one randomly selected trial per position. Results demonstrated that ELR values were highest at the bottom of the movement in all positions, and that third and fourth positions yielded higher overall ELR values than second position throughout the movement. The researchers suggested limiting excessive repetition of *grand pliés*, particularly in third and fourth positions.

Couillandre, Lewton-Brain, and Portero (2008)[56] conducted an intervention study involving the *demi plié*, using mental imagery to affect muscle use and movement strategies. EMG data were collected on four lower limb muscles: vastus lateralis, biceps femoris, tibialis anterior, and soleus. Additionally, a muscle tester and accelerometer were used, and measurements at the lateral knee were collected with a goniometer. Participants were seven female professional ballet dancers, who were pre- and post-tested performing movement in two conditions: (1) a free-standing first position *demi plié*, and (2) a jump in first position. The intervention consisted of biomechanical and anatomical explanations of the movements, followed by mental imagery techniques designed to encourage better alignment, more efficient muscle recruitment, and improved movement function. Analysis consisted of a paired *t*-test if normality passed and a Wilcoxon signed rank test if normality failed.

For the *demi plié*, there was no significant difference in maximum knee flexion after the intervention. There was a significant difference in biceps femoris activity, which was more active after the intervention. For the jump condition, there was no significant difference in height of the jump or maximal vertical acceleration after intervention. The biceps femoris activity increased, especially in the lowering phase before the jump, and an increase in tibialis anterior activity occurred in the ascending phase before the jump, along with a decrease in vastus lateralis activity. Sagittal variation ("bucking" in the spine) was reduced post-intervention.

Relevé

Albers, Hu, McPoil, and Cornwall (1992/93)[68] investigated foot plantar pressures in a variety of conditions. Participants were 10 female ballet students who performed three trials of each of the following: (1) self-paced walking barefoot, (2) self-paced walking in pointe shoes (3) *elevé en pointe* (straight legs in second position to rise), (4) *relevé* (a forward step, followed by *plié–relevé en pointe*) onto the dominant leg. The order of the last two was randomized. Trials were done on a forceplate and a 10-meter walkway. Analysis consisted of taking the mean of the three trials for each condition, and then performing within-subjects ANOVA, followed by Tukey's post-hoc comparisons. There was a significant difference between walking barefoot and the other three conditions, and between walking in shoes and the *relevé* condition.

Dozzi and Winter (1993/94)[72] conducted a biomechanical analysis of the foot when rising to full *pointe*. Data were collected with video using markers on the foot and ankle and a forceplate. Participants were two female professional dancers who performed three trials of a slow rise to full *pointe* and lowering. Analysis consisted of computer calculations of forces. The main result was that the intrinsic muscles of the foot crossing the metatarsal-phalangeal joints work 2.5 to 3 times harder than those crossing the ankle during the rising phase. They recommended that dancers only wear *pointe* shoes when *pointe* work is required.

Yoshida and Kuno-Mizumura (2003)[80] examined the effect of fatigue on a *relevé* test through EMG analysis. Electrodes were placed on the medial gastrocnemius, lateral gastrocnemius, soleus, and tibialis anterior. Participants were six female Japanese dance students and seven females with no dance experience. As this paper was a conference abstract, information was limited. There was no indication that maximum contractions for the muscles in question were determined, nor was the method of analysis described. All participants performed the *relevé* to exhaustion. There was no significant difference between the two groups in number of *relevés* performed. Dancers had greater range of motion at the ankle, and the concentric phase showed an increase in EMG activity of all muscles in dancers. The researchers state that the soleus is more fatigue resistant in dancers and that these differences may be the result of training.

Massó, Germán, Rey, Costa, Romero, and Guitart (2004)[24] conducted a study of muscle activity during *relevé*, comparing parallel and externally rotated positions. Data were collected with a four-camera Elite Motion Analyzer system and EMG recording the following muscles: peroneus longus, soleus, lateral gastrocnemius, medial gastrocnemius, and abductor hallucis. Participants were 18 female professional ballet dancers who performed the following movements: *relevé* in parallel (sixth position), *relevé* in first position turned out, and *relevé* in first position turned out "without any active muscular control and with foot pronation" (p102). Number of trials per condition was not reported. For analysis, means and standard deviations were computed. Intra-subject comparisons were made using the Wilcoxon test, and EMG data were analyzed through direct observation. No maximum contractions were collected, and no statistical analysis was performed on EMG data. Results indicated the following: plantar flexion angle was statistically higher in sixth position than in first; medial gastrocnemius was more active in *relevé* in first position, but the abductor hallucis was more active in sixth position; with foot pronation, peroneus longus and gastrocnemius muscles were most active.

Kadel, Donaldson-Fletcher, Segal, Falicov, and Orendurff (2004)[22] investigated muscle activity during four movements *en pointe*: rise to *demi pointe*, *elevé* (rise to full *pointe*), *piqué passé* (stepping onto one foot *en pointe*), and a two-foot spring to *pointe*. Data were collected with EMG, motion analysis using a 10-camera Vicon system and 38 reflective markers, and two forceplates. Electrodes were placed on the medial gastrocnemius, lateral soleus, peroneals, and tibialis anterior. Four female professional ballet dancers performed three trials of each condition, standing with one foot on each forceplate. Data were analyzed in Polygon, and trials were averaged, with maxima and minima recorded. Results indicated the following: plantar flexion was greatest following the *elevé* rather than the other conditions; muscle activity for all four muscles was greatest during the rise to *pointe* but decreased once the dancer arrived *en pointe*; soleus activity was low during the rise to *demi pointe*, but during the rise to full *pointe* was similar to its activity for the *piqué* and the spring to *pointe*.

A similar study by Kadel and Couillandre (2007)[87] was reported in an abstract for a conference presentation. Their purpose was to compare joint angles, moments, and muscle activity during three movements *en pointe*: rise to *pointe* in second position, *piqué retiré* (stepping onto one foot *en pointe*), and a two-foot spring to *pointe*. Data were collected with EMG, motion analysis using a 10-camera Vicon system and 38 reflective markers, and two forceplates. Electrodes were placed on the stance leg on the medial gastrocnemius, lateral gastrocnemius, soleus, peroneals, and tibialis anterior. Sixteen female professional ballet dancers stood with one foot on each forceplate and performed three trials of each of the three movements in two conditions, supported and unsupported. Order of the trials was randomized. Analysis consisted of *t*-tests. Results indicated no significant difference in maximal plantar flexion angle between supported and unsupported conditions for the three movements. Muscle use at the barre was significantly different for most of the muscles tested than without the barre. For soleus and tibialis anterior, there was more activity at the barre, but for peroneals and medial gastrocnemius, there was less activity at the barre.

Bartolomeo, Sette, Sloten, and Albisetti (2007)[21] reported their research in a conference poster presentation, and not all information was presented. They collected EMG data on the tibialis anterior, medial gastrocnemius, and rectus femoris for 101 male and female ballet and modern dancers performing *relevé* on *demi pointe* and *pointe*. Data were evaluated using the normalized ARV (average rectified value) index. There was no report of maximum contractions being collected. The researchers stated that *demi* and full *pointe* have different muscle activation patterns, and there were also gender-based and individual differences, but no statistical analysis was done and no other conclusions were stated.

Lin, Su, and Wu (2005)[23] compared dominant and non-dominant sides during *relevé en pointe*. Data were collected using a five-camera Hires motion analysis system, with 19 reflective markers, and two forceplates. The participants were 13 female ballet dancers with over 5 years of training, and they were all right dominant. The participants did three static trials (standing in turned-out first position) and five trials of rising to full *pointe*. Three movement trials were used for analysis, which consisted of *t*-tests. Results suggested that the dancers had similar range of motion and excursion patterns during the movement, but different initial moment exertions on the two sides and significantly different peak moments. The researchers stated that dancers were more skilled at controlling the ankle on the dominant side, and they suggested that the dominant side was the primary control of balance throughout the movement.

Passé

Bronner and Brownstein (1998)[25] conducted the first study looking at the *passé*, with the goal of providing normative data in skilled dancers for this multi-joint movement requiring stability and balance. Data were collected with a two-camera motion analysis system with 12 reflective markers. Participants, five male and five female professional dancers, performed the movement in two conditions: (1) a series of six consecutive *passé* movements with each leg, and (2) a series of 12 *passé* movements alternating legs. The entire process was executed two times. Analysis consisted of measurements of temporal sequencing, marker displacements, and various velocities of trunk and limb markers. Results indicated that dancers are consistent in their execution of the task and that trunk translation precedes limb activity.

Sandow, Bronner, Spriggs, Bassile and Rao (2003)[48] compared expert dancers and beginners executing the *passé* from bipedal stance, reported in a conference abstract. Data were collected with a five-camera motion analysis system; no other information about the system was reported. The participants, 10 elite female dancers and 10 novice female dancers, performed five trials of the movement, all with the right leg as the gesture leg. Means and coefficients of variation for each individual were calculated over the five trials, and grand means and standard deviations were calculated for each group. Results suggested that the elite dancers were more consistent in temporal and spatial elements than the beginners. The elite dancers were able to maintain unilateral balance for a longer period of time and demonstrated anticipatory postural control not seen in the beginners.

Bronner and Ojofeitimi (2006)[52] examined gender and limb differences in the execution of the *passé*. Data were collected with a one-camera Peak Performance motion analysis system, with 12 reflective markers placed bilaterally on the trunk and limbs. A power analysis was conducted, indicating the minimum participant number was six. Six male and six female professional ballet and modern dancers executed six consecutive *passé* movements from turned-out first position with the right leg and six with the left leg. The entire sequence was repeated. Each *passé* sequence was approximately 1.2 seconds. Analysis consisted of interclass correlation coefficients, calculations of means and standard deviations, and two types of 2×2 ANOVA—between (gender) and within (limb). The latter looked at both right versus left and preferred versus non-preferred. Results indicated no limb differences. Gender differences were identified in peak hip angular displacement, with women demonstrating greater hip flexion than men. Overall, there was similar coordination in males and females and in limbs, most likely due to extensive, symmetrical training of a highly specific task.

Degagé

Mouchnino, Aurenty, Massion, and Pedotti (1992)[46] compared the *degagé à la seconde* in experienced dancers and naïve participants. Data were collected with a one-camera Elite motion analysis system with 14 reflective markers on the trunk and lower limbs, one forceplate, and EMG electrodes placed on the erector spinae, rectus abdominus, gluteus maximus, tensor fasciae latae, vastus lateralis and vastus medialis (paired), biceps femoris, lateral and medial gastrocnemius and soleus (grouped), and tibialis anterior and lateral peroneals (grouped). Fourteen male and female volunteers were divided into two groups: five experienced modern dancers, and nine naïve participants. Participants performed four *degagés* with each leg as fast as possible. In the first paradigm, they were given no instructions regarding the trunk; in the second paradigm, four naïve participants were asked to keep the trunk as vertical as possible. Analysis consisted of *t*-tests for both paired variables and two populations.

Results indicated several differences between experienced dancers and naïve participants. Dancers exhibited no adjustment phase, whereas the naïve participants had a long adjustment phase, the period of time between the initiation of the gesture, and arrival on balance on the supporting leg. Dancers had a feed-forward strategy, with muscles of the supporting leg activating prior to the gesture leg muscles; the strategy of the naïve participants was reactionary. Dancers used a translation strategy in the pelvis to shift the center of weight over to the supporting leg; naïve participants used an inclination strategy and tilted the pelvis to achieve weight transfer. It is suggested that training may be responsible for altered strategies in experienced dancers.

Lepelley, Thullier, Koral, and Lestienne (2006)[26] conducted a study investigating what they call the *jeté*, which is normally terminology for the leap, an elevation step. However, they only analyzed the forward brushing action of the leap from first position turned out, and then returning to first position, which more closely resembles the action of a *degagé*. Data were collected using a four-camera Vicon motion analysis system, with 17 reflective markers. EMG activity was collected on 18 muscles as follows: electrodes were placed on both legs on the biceps femoris, rectus femoris, vastus lateralis, vastus medialis, tibialis anterior, lateral gastrocnemius, soleus, and on trunk and pelvis muscles on the left or right sides in different participants on lumbar extensors, rectus abdominus, psoas, and gluteus maximus. For EMG analysis, researchers used the percentage of dynamic maximum during trials. Participants were six female ballet dancers, four advanced students and two professionals. They performed 10 trials of the task with the right leg. A major finding was that the EMG activity of several of the muscles was minimized just before initiation of the trial and at the start of the reversal phase. The researchers offered suggestions for controlling multi-muscle and multi-joint systems in dance.

Wieczorek, Casebolt, Lambert, and Kwon (2007)[65] investigated knee mechanics during *degagé à la seconde* at barre and center and looked at the standing knee from three spatial perspectives. Data were collected on one female professional dancer with a 3D motion analysis system using 30 reflective markers, and two forceplates, with each foot positioned on a different forceplate. The participant performed two trials of a *degagé à la seconde* in each condition, with and without use of the barre; only the second trial was used for analysis. Analysis was a 3D inverse dynamics approach used to calculate resultant joint movements for the supporting (left) leg. Results indicated that different strategies were used for the *degagé* when performed with and without a barre. The researchers suggest that there is hamstring co-contraction at the supporting knee without the barre that is not present when the barre is used. Amount of torque at the supporting knee was less without the barre for support.

Développé

Monasterio, Chatfield, Jensen, and Barr (1994)[45] did a follow-up investigation to the work by Mouchnino et al. (1992),[46] examining differences between trained dancers and nondancers performing a low *développé à la seconde* starting at the ankle and ending just off the floor. Data were collected with a two-camera Watsmart 3D motion analysis system, with reflective markers on eight locations. Fourteen EMG electrodes were placed bilaterally on the medial hamstrings, vastus medialis, erector spinae, lower abdominals, trapezius and lower sternocleidomastoideus, and on the right (stance) leg only on the gastrocnemius and tibialis anterior. Participants were 10 intermediate college dancers with ballet and modern training and 10 nondancers in the same age group. Ten trials were executed in each of three conditions, all with the left leg as the gesture leg: slow speed, self-paced speed, and fast speed. Analysis was a $2 \times 4 \times 10$ ANOVA (group by muscle by trials). Results indicated that postural muscle activity (hamstrings, quadriceps, tibialis anterior, and gastrocnemius) occurred prior to the voluntary movement in the dancers in the fast trials only. Kinematic data were inconclusive.

Bronner, Brownstein, Worthen, and Ames (2000)[41] compared various levels of dancers executing arabesque. This article was a conference abstract, and there was not extensive detail. Data were collected using a 3D motion analysis system. Thirty participants were divided evenly into three groups based on ballet placement by faculty at an international dance school: professionals (minimum of 10 years of dance training), advanced, and beginner-intermediate. No information was given about methods or analysis. Results suggested that frontal plane postural control and execution of the transitions between movement phases varied greatly from expert to student dancer. Students appeared to focus more on the gesture limb, at the exclusion of trunk control and smooth execution.

Wilmerding, Heyward, King, Fiedler, Stidley, Pett, and Evans (2001)[67] compared muscle use during the *développé devant* from fifth position at barre and in the center. EMG data were collected on the vastus lateralis and hamstrings of the gesture leg, and on the abductor hallucis and tibialis anterior of the standing leg. Maximum isometric voluntary contractions were collected on each muscle for use during analysis. Participants, 18 professional and advanced female dancers, performed five trials in each condition (barre and center) in random order. Analysis was a mixed-effects four-factor ANOVA, followed by Tukey's post hoc tests. Results indicated that the standing leg muscles showed the greatest variance between conditions. Activity of the abductor hallucis and tibialis anterior for the standing leg was significantly greater in the center than at the barre, suggesting that postural responses for balance may not be well trained at the barre.

An abstract by Spriggs, Bronner, Brownstein, and Ojofeitimi (2002),[49] submitted to the International Association for Dance Medicine & Science's Annual Meeting, described an investigation of variations in movement smoothness between groups of various levels performing *arabesque*. Data were collected using a Vicon five-camera motion analysis system. Thirty male and female participants were divided into three groups: beginner, advanced, and expert. 2D and 3D "cost jerk" (defined as rate of change of acceleration) was determined for comparison across groups. No information was given about number of trials. Results indicated a reduction in values from beginner to expert, suggesting that increased "smoothness" develops with higher levels of training.

An abstract by Ahonen and Hobden (2003),[88] submitted to the International Association for Dance Medicine & Science's Annual Meeting, did not summarize a research study, but rather described the biomechanics of *arabesque* and *attitude devant*. The focus was to examine the closed kinetic chain of the standing leg compared to the open kinetic chain of the gesture leg in two dance movements. Further, they discussed the spine and back muscles, and how they function in support of the lower extremities, for best execution of *arabesque* and *attitude devant*.

Feipel, Dalenne, Dugailly, Salvia, and Rooze (2004)[27] focused on the lumbar spine, during execution of *arabesque*, *développé à la seconde* with and without barre, and *pied-en-main* at the barre, in which the gesture foot is held by the ipsilateral hand and lifted as high as possible. Participants were 25 professional or semiprofessional ballet dancers, 17 female and 8 male. Each movement began from the turned-out first position and was executed three times on each side. Data were collected with a Spine Motion Analyzer mounted on the dancer using straps at the thorax and pelvis and with photography. Dancers also completed a questionnaire about their dance and medical history. Analysis consisted of Kruskal-Wallis median ANOVA and Wilcoxon matched-pairs test. Results indicated that pain and injury in the lumbar area significantly affected shoulder inclination during *développé à la seconde* with and without barre and *pied-en-main* at the barre. However, there was no correlation between posture and lumbar motion during the tasks. The researchers concluded that height of the leg in all of the dance movements examined depended more on hip flexibility than a spine contribution.

Torres-Zavala, Henriksson, and Henriksson (2005)[64] also examined *développé à la seconde* with and without the barre. Data were collected with an eight-camera Elite motion analysis system, using 22 reflective markers, and two forceplates. Twelve professional ballet dancers (10 women and 2 men) performed five trials in each of the two conditions, with and without the barre, and completed a questionnaire. In this abstract, little information was given about analysis. Results indicated that center of pressure displacement was different in the two conditions and that barre may impede the development of correct postural control for this task.

Rond de Jambe

Thullier and Moufti (2004)[51] examined the multi-joint coordination of *rond de jambe*, performed just off the floor. Data were collected with a four-camera Vicon motion analysis system using 17 reflective markers. Participants were six elite classical dancers (experts) and six gymnasts with no dance training. Participants executed the movement 10 times. Analysis included Mann-Whitney U-tests. The researchers concluded that although both groups were equally stable, dancers were more successful in accurately representing the shape and spatial orientation of the movement. They also stated that there are underlying rules or patterns in the nervous system's ability to integrate multiple degrees of freedom, i.e., to master and execute multi-joint coordination.

Wilson, Lim, and Kwon (2004)[50] profiled the *grand rond de jambe en l'air en dehors* (front to back) and compared skilled versus novice ballet dancers. Data were collected using six digital Panasonic camcorders, with 11 reflective markers, and digitized using the Kwon3D software. Ten university dance students were divided into two equal groups, identified as skilled or beginner by two ballet faculty members. Participants executed three trials of the movement, instructed to keep the gesture leg (right) at a 90° angle from the standing leg and torso. The best trial, determined by consistency of height and stability, was selected for analysis. Formulas were computed, including pelvic and trunk motions, and analyzed using *t*-tests for comparing the two groups. There were significant differences in vertical angle of the gesture leg (skilled dancers' gesture legs were above 90° and beginners below) and pelvic tilt (skilled dancers demonstrated more pelvic motions than beginners), but no significant differences in trunk motions were found. It was concluded that skilled dancers use a pelvic strategy to execute this dance movement.

Kwon, Wilson, and Ryu (2007)[28] conducted a further investigation of the gesture and stance legs in *grand rond de jambe en l'air en dehors*. Data collection used six digital Panasonic camcorders, multiple reflective markers, the Kwon3D software for digitizing, and a forceplate for ground reaction forces. Participants, eight skilled and eight novice female ballet dancers, performed the *grand rond de jambe* in two conditions set to music: at 90° and at 105°. Standard inverse dynamics procedures were used to compute hip net joint moments and normalized to each participant's mass. Analysis was a two-way, mixed-design ANOVA, and post-hoc comparisons of the group means were performed with the Sidak adjustment. The researcher concluded that muscular strength, especially in the gesture leg, was not what prevented the beginners from using the strategy of the skilled dancers. A second observation was that increased demand (vertical leg angle) actually put less demand on the hip muscles of the standing leg. Finally, the hip abductors were identified as highly important in the execution of this task. The researchers recommended placing more emphasis on the standing leg in the training process.

Grand Battement

Ryman and Ranney (1978–79)[15] examined the *grand battement devant* performed unsupported, i.e., without use of the barre. While many educators and researchers discuss this study as a comparison between executing this movement with and without the barre, no trials were performed or analyzed using the barre. Data were collected with single-camera cinematography, recording the movement with markers and fins on the dancers' bodies, forceplates, and EMG electrodes placed on the rectus femoris, vastus medialis, gluteus maximus, biceps femoris, sacrospinalis, and rectus abdominus. Participants were four female advanced ballet dancers from an internationally recognized professional school. Dancers executed three trials of the *grand battement*, and the middle trial was used for analysis. Data for MVCs (maximum voluntary contractions) were also collected for EMG analysis. The film was viewed on a Numonics Analyzer to determine body-segment displacements, and all analysis was descriptive.

The researchers[15] suggested that many of the suppositions dance educators make in teaching this movement are not supported by the results of this study. The gesture knee slightly flexes and the leg loses contact with the floor early in movement initiation. The pelvis rotates (posterior tilt), the lumbar spine flexes, and turnout is not maintained in the gesture leg, most likely because gluteus maximus activity diminishes as the leg height increases. Skilled dancers, however, did not make these torso and pelvic accommodations to such a degree that the torso appears to collapse and shorten. In other words, these compensations must be kept to a minimum for aesthetic reasons. The participants hyperextended the knee at the height of the battement, giving the illusion that the whole leg went higher. The EMG data were highly variable, despite homogeneous training in the participants. The researchers suggested that due to this variability, it is ineffective to dwell on specific muscle activation, but rather teachers should use imagery and focus on whole body actions to encourage the desired movement.

There was further theoretical discussion of how the results compared to *grand battement* when executed at the barre.[15] The researchers observed marked weight shift in the sagittal plane in their participants, which they suggested was not executed when using the barre. They suggested that care must be taken so that an overdependence on the barre does not develop at the expense of a responsive use of the torso.

In Ranney's chapter in *The Science of Dance Training* (1988),[84] he described an article by Ryman and Ranney entitled "A preliminary investigation of skeletal and muscular action in the *grand battement devant*," published in *Dance Research Journal*. However, no article by this title exists in the literature, and therefore it has been concluded that this discussion was referring to the same article described above.[15] Interestingly, Ranney gave some additional information not in the published article. He made reference to eight additional participants from another dance school. Results were consistent with the previous conclusions: i.e., the gluteus maximus must decrease activity despite the teachers' encouragement to maintain a high level of contraction in this muscle, the gesture leg loses external rotation at the height of the *battement*, and the pelvis rotates 30° into posterior pelvic tilt. He supported previous recommendations that teachers reconsider how they teach this task.

Bosco Calvo, Iacopini, and Pellico (2004)[29] examined the *grand battement devant* and *à la seconde* in three conditions: eyes open, eyes closed, and with imagery. Data were collected with a six-camera Peak Motus video system. Participants were professional dancers and full-time dance students with ballet or contemporary backgrounds. Number of participants and method of analysis were not stated in this abstract. Results indicated that there was significant posterior pelvic tilt in the *grand battement devant* and significant lateral pelvic motion in *grand battement à la seconde*, supporting previous research on these dance movements.

Wang, Huang, Hsieh, Hu, and Lu (2008)[30] examined the *grand battement* in Chinese dance. This paper was a brief translation of an article in Chinese, and information was limited. Data were collected using cinematography, EMG electrodes on the erector spinae, gluteus maximus, and biceps femoris, and a goniometer was used to measure hip and trunk flexibility. Participants were 22 female dancers who performed eight trials of the selected movement. Means and standard deviations were calculated, but no other information was given regarding analysis. Results indicated that there were differences between the preferred and nonpreferred leg, but unfortunately due to translation issues, no other results can be reported.

Arm Movements

The only study in the literature examining the characteristics of arm movements in dance was conducted by Kuno-Mizumura, Seta, and Mizumura (2004).[31] They compared nine advanced female ballet dancers to ten nondancers, using one-camera motion analysis with markers placed on the upper extremities. Participants performed the swan arm movements from the ballet *Swan Lake* at three tempos (slow, base, and fast trial), doing six trials at each speed. The third trial of each tempo was used for analysis, done by *t*-tests. Results indicated that in dancers, the elbow moved first, and there was a wide range of movements at the elbow and wrist. The nondancers performed the movement with little change in joint angles. The researchers attributed the differences to training.

Forward Stepping

In a conference abstract, Krasnow, Chatfield, and Blessing (2002)[43] compared three elite and three novice dancers executing a shift of weight in space from a one-legged balance on the right leg, followed by a forward step, resolving on a one-legged balance on the left leg. Data were collected using EMG electrodes placed bilaterally on the abdomen and erector spinae, a four-camera Peak Performance motion analysis system with markers placed along the plumb line of the body, and two forceplates under the initial stance leg and the resultant balancing leg. Participants were tested on two separate days to test for day-to-day variability. Analysis was descriptive based on visual examination, looking at EMG ensemble graphs of each participant's trials, consisting of 15 trials per participant per day.

Results indicated that elite dancers' alignment was less variable than the beginners' alignment, and further, the elite dancers' verticality improved after the shift of weight, while the beginners' verticality deteriorated. There were differences between the EMG data of the two groups: the elite dancers had a clear abdominal muscle activation pattern (right abdominals were active in the initial balance, a bilateral burst occurred during the weight shift, and left abdominal activity was found in the final balance), while the beginners' use of abdominals was erratic. These differences may indicate a training effect.

Ojofeitimi, Bronner, Spriggs, and Brownstein (2003)[47] investigated elite and untrained dancers executing pedestrian movement requiring weight shift, resolving in a one-legged balance. This study was described in an abstract and complete details were not available. Data were collected with a five-camera motion analysis system and a forceplate. Participants were 17 elite dancers and 17 nondancers (20 female, 14 male). Independent *t*-tests were performed to assess differences between the two groups. Although there were no significant differences in reaction time or joint movement sequences, the elite dancers maintained verticality and had better control of the gesture limb during the balance.

Chatfield, Krasnow, Herman, and Blessing (2007)[42] did follow-up analysis and discussion on the their previous 2002 study.[43] Examination of the ensemble graphs indicated that elite dancers and beginners both demonstrated a similar wave pattern for anterior/posterior sway of the torso during the forward step. Prior to stepping, participants performed a *plié* on the supporting leg, and during this phase there was anterior sway. During the shift of weight, the torso sway was posterior. While both groups demonstrated this pattern, the anterior sway for the elite dancers was twice as large as their posterior sway, but the opposite was the case for the beginners. At resolution, the elite dancers were close to vertical, whereas the beginners were considerably posterior to the vertical line. The surprising result was that the overall amount of sway was the same for both groups, suggesting that elite performance is not more "rigid" with less dynamic accommodation than beginners during shift of weight.

EMG analysis[43] focused on bursts of activity, not amplitudes, and therefore no data for MVCs (maximum voluntary contractions) or MVICs (maximum voluntary isometric contractions) were collected. While both elite and novice dancers showed consistent abdominal and erector spinae activity, there were different patterns observed. Elite dancers had unified single bursts of abdominal activity, whereas beginners had double burst patterns. Overall the elites demonstrated abdominal patterns that were more synchronized bilaterally and better timed for control during the resolution balance phase. Finally, looking at individual data, there was much greater variability between novice dancers than between elite dancers. The kinematic data of the three beginners was so variable that the ensemble data did not resemble two of the three individual graphs, suggesting that it may be necessary to look at individual rather than group data to gain a full understanding of dance movement strategies.

Turns

An early master's thesis by McMillan (1972)[8] compared the execution of the *pirouette* by three levels of dancers during preparation, turn, and conclusion phases of the turn. Data were collected using a 16-mm movie camera (frontal and sagittal views), a clock to time the various phases, a yardstick near the dancer, and a frame-by-frame microfilm reader. Participants were three professional dancers, three semi-skilled university dance majors, and three beginners. They performed three *pirouettes* from fourth position in each of the two views. Analysis consisted of tracings made on selected frames, drawings made from these tracings, and descriptive analysis. Results showed that: (1) the preparation phase is more similar for the three groups than the turn and conclusion phases, although professional dancers demonstrated larger movement and took less time in the preparation phase than semi-skilled and beginner dancers; and (2) there was a difference in spotting technique, arm position, right foot placement, and acceleration during the turn, and it was the skilled dancers who were different than other two groups.

Laws and colleagues conducted several studies examining turns in dance.[12,32,33,63] The early studies shared certain research parameters: single-subject design, photography, or videography to collect data, and physics formulas for analysis. In his 1978–79 study, Laws[12] measured torque and resulting angular momentum of a dancer initiating a turn. In addition to photography, a platform and oscilloscope were used for data collection. The participant, a female professional ballet dancer, executed a series of three types of turns: *pirouette en de hors*, *arabesque* turn, and *pirouette an dedans* with the gesture leg in low second position. Fifty trials were completed over 2 days. Laws described the turns qualitatively, and made suggestions about how to do these turns with correct technique and efficiency.

In the 1986 report, Laws[32] examined the mechanics of the *fouetté* turn, collecting data with videography from the front and directly overhead. The participant, one advanced ballet student, performed a supported turn, sometimes called a finger turn, where the partner supports the dancer using one finger placed overhead. Laws constructed a geometric model of the turn and described a correlation between three different techniques in determining the length of the pause during consecutive turns.

Laws and Fulkerson (1992/93)[33] investigated the *pirouette*, collecting data on video with one professional ballet dancer. They used formulas for measuring results and concluded that the number of turns was dependent on the initial momentum and that balance limited the number of turns possible.

Meglin and Woollacott (1992)[89] used neuroscience research to create a theoretical model for turns. While not a research article, this paper is included in this review due to its relevance to the body of research examining turning techniques. Their conclusions were summarized in the following five ideas: posture anticipates gesture, interacting systems allow both preset and changing strategies, peripheral inputs allow immediate corrections, the final position is programmed in advance, and differing areas of the brain are involved in the execution of turns.

Sugano and Laws (2002)[63] investigated the *pirouette*, integrating principles of physics and pedagogy in their analysis. For data collection, they used a 3 × 4 foot platform and a bathroom scale to measure the weight on front foot prior to the turn. Participants were 25 collegiate dance students of varying levels of training, who performed controlled multiple turns. A total of 190 turns were executed. The researchers measured the width of the fourth position preparation, comparing successful and nonsuccessful attempts. They charted the results and found the following: (1) the pirouettes improved when the width of fourth position preparation was increased; and (2) the initial proportion of weight on each foot must be controlled, which was best for the intermediate dancers.

Elevation Work

Of all the dance movements investigated with biomechanics tools, elevation steps are by far the most researched. Numerous studies investigate and analyze vertical jumps, leaps, turning elevation steps, and multiple variations. Also included in this section are studies examining impact forces in tap and flamenco dance. Although the steps executed in these studies would not technically be considered jumps in a dance genre such as classical ballet, the researchers investigated similar impact and loading forces of striking the floor and effects on the joints of the body.

1970s: Early Work Profiling Technique

Two master thesis studies investigating elevation work date to the mid-1970s.[4,5] It is noteworthy what these investigators were able to discover with rudimentary equipment and so little previous research for guidance.

Buchman (1974)[4] investigated the technique of performing the *tour jeté* during the takeoff phase, jump and accompanying rotation phase, and the landing phase. Similar to the McMillan *pirouette* study (1972),[8] data were collected using a 16-mm movie camera (side view), a clock to time the various phases, a yardstick near the dancer, and a frame-by-frame microfilm reader. Participants were three professional dancers, three semi-skilled university dance majors, and three beginners. The three professional dancers performed four *tour jetés*, and the other six dancers performed three *tour jetés*. Analysis consisted of tracings made on selected frames and drawings made from these tracings. Each group's tracings were superimposed to create one image; Buchman then did descriptive analysis of the line drawings and measured angles. There were marked differences between groups. The skilled group executed the *tour jeté* as described by Vaganova, except for the rotary component, which began as the participant left the ground and not in air. The skilled participants minimized horizontal traveling by leaning away from the direction of travel during the takeoff phase, thus enhancing vertical elevation. The semi-skilled and novice dancers used erect and forward leans, resulting in less vertical elevation and more horizontal traveling.

Gaffney (1976)[5] wanted to determine select movement patterns in the performance of *grand jeté* by one professional dancer. Data were collected with two motion picture cameras, a Locam and a Bell & Howell. The dancer was filmed performing three *jetés* from the frontal and sagittal views, and then three *jetés* from the sagittal and overhead views. White markers on black clothing were placed on body landmarks. Tracings were made using a Vanguard Film Analyzer, and analysis was descriptive. In general, the participant performed the *jeté* as described in the literature, and all trials were similar. There were the following variations from the literature: (1) as described, the arms should open to the second position and remain side, but the dancer used a backward and upward motion to propel the body forward; (2) there was slight spine and shoulder movement, although the literature suggests these areas should not move; and (3) the front gesture leg is supposed to reach a 90° angle, but the participant's front leg did not come close to this angle.

Ryman (1978)[14] analyzed six elevation steps performed by one professional ballet dancer: *grand jeté en avant, pas de chat jeté, temps levé en avant en arabesque, grand ballonné en avant, grand fouetté sauté,* and *grand jeté dessus en tournant* (commonly called *tour jeté*). Data were collected using cinematography, and analysis consisted of quantitative evaluation using traces, tables, and graphs, plus qualitative description of the *grand jeté dessus en tournant*. Four results emerged from this study that contradicted previous pedagogical theories about elevation work: (1) it is a false assumption that deeper *pliés* yield higher elevation, and in this study, the moderate *pliés* yielded the best results; (2) suspension at the top of an elevation step is an illusion, i.e., the ascent and descent are one continuum; (3) for turning elevation steps, the turn must begin at pushoff, not at top of elevation; and (4) the foot sickles at moment of pushoff.

Hinson, Buckman, Tate, and Sherrill (1978)[11] also investigated the *tour jeté*, which they called the *grand jeté en tournant entrelacé*. For this study, data were collected using a camera, tape placed on the joints as markers, and a yardstick included in the film near the dancer for measurement of distances. Three professional ballet dancers performed the *tour jeté*, but it was not clearly stated if they did multiple trials. Tracings of the body were made on the film on seven selected frames and visually analyzed. This research supported the conclusions of Buchman (1974),[4] stating that the *tour jeté* was executed similar to the description in the Vaganova literature, except for the rotational timing.

1980s: Work Profiling Technique

The master's thesis research by Shea (1981)[10] examined biomechanics of body rotation during the *fouetté sauté* (a turning elevation step on one foot) and compared the strategies of professional dancers to the teaching instructions suggesting that dancers initiate the turn at the height of the jump. Three female professional ballet dancers were filmed with cameras from a side and overhead view, with various types of markers on the body, including white tape strips, black and white square markers, and black tape bands. A Recordak microfilm reader was used for analysis. Participants executed three trials of the *fouetté sauté*, using classical ballet arms. Shea did a descriptive analysis of one selected trial for each participant, using the criteria of the best two-camera view and clarity, and compared the positions of the three participants at key points (e.g., takeoff, height of jump, landing). The most notable difference between the three participants was the sequence of body part rotation, which varied greatly with each participant, and the degree of angular rotation. The researcher suggested the following strategies to create the illusion of turning in air: (1) maintain the original facing during takeoff as long as possible, (2) generate angular momentum before takeoff, and (3) timing of the opening of the arms should be rapid, but as late as possible in the movement. Finally, it is suggested that it would be beneficial for teachers to understand the difference between the illusion and aesthetic quality the dancer wants to create, and the biomechanics necessary to achieve this effect.

The master's thesis research by Becker (1985)[69] examined the kinetic and kinematic factors of landing technique at the end of a jump and at the end of a leap to learn about impact forces. Data were collected using two cameras vertically stacked, two timing light generators, a Lafayette film analyzer to select frames of value to the investigation, and a forceplate. Fifty-six female and nine male volunteers were from touring university dance groups, amateur groups, and professional dance companies. Participants performed three trials each of two conditions: a dance jump (first position vertical jump) and a dance leap (*glissade*) executed at right angle to the cameras, landing in the center of the forceplate. Analysis consisted of calculating means and standard deviations, ANOVA, Pearson correlation, multiple regression, and descriptive methods. Conclusions included the following: (1) the distance of vertical descent did not predict impact landing forces for either the jump or the leap; (2) landing technique concentrating on artistic quality did not develop low impact landings; and (3) in general, dancers flexed the knee 120° at the end of the jump. The mean and upper limit impact landing peak forces were much higher in this study than in previous studies.

Wiley (1987–88)[40] investigated the *saut de basque*, another elevation step common in the classical vocabulary. Data were collected with a camera, and tracings were made on the film every 20 frames. One male professional ballet dancer performed 15 trials. For analysis, the movement was broken down into five phases, and the balletic model was compared to a biomechanical model. Wiley described multiple errors that can occur when executing this step, too numerous to name in this review. Examples included too much bounce in the run (approach phase), too deep or too shallow a *demi plié* (preparation phase), bending the gesture leg during the swing (take-off phase), lack of simultaneous extension of both arms and both legs (flight phase), and overall misalignment (landing phase). Wiley concluded by stating that it is essential to use scientific analysis to improve dance pedagogy.

Dozzi (1989)[34] compared the biomechanics of dancers' jump landings with varying pedagogical directions. Data were collected using a force platform with a heel switch to determine heel contact and an accelerometer on the tibia just below the knee. Participants were 10 advanced ballet students. They performed five continuous jumps in first position turned out, cued to aim for maximum height in three conditions: their "normal" jump landing technique (NOR), forced heel contact or what is called pressing the heels into the floor on each landing (FHC), and intentionally allowing no heel contact (FNHC), with the order of the three sequences randomized. For analysis, the first, last, and any jumps not meeting the criteria for the condition were discarded. Two jumps in each condition were analyzed by determining the means and standard deviations of elevation and other joint factors. Results indicated the following: (1) for the NOR condition, only 1 in 20 jumps did not have heel contact; (2) in FHC, there were more heel double-strikes, considered to increase the potential for injury; (3) mean peak forces were greatest in the FHC condition; (4) elevation was no different in the three conditions; and (5) there was greater shock absorbency in the NOR and NFHC conditions than in the FHC condition, suggesting to the researchers that the teaching cue of pressing the heels to the floor in jump landings is not a good teaching tool, but rather the light heel contact these advanced dancers demonstrated in their normal technique is a better strategy.

As with the turn studies, Laws and colleagues have investigated various elevation steps using physics principles and analysis.[90–92] Laws and Lee (1989)[90] analyzed the *grand jeté* using videography. The participant was one professional dancer, who performed 10 trials. Analysis consisted of physics formulas to calculate aspects of the *grand jeté* such as velocity and momentum. Results included the following: (1) the time that the head and torso move horizontally at the top of the *jeté* can be more than half of the flight time; (2) the *jeté* is less effective if turnout of the push-off foot is maintained during the take-off phase; and (3) about half of the energy of the total *jeté* is expended in the take-off. The main focus of this article was to demonstrate how knowledge of physics principles could assist the dancers in improving execution of the *grand jeté*.

Li and Laws (1989)[91] analyzed *da she yan tiao*, an elevation step in Chinese dance. It is included here due to its similarity to the *grand jeté* and the use of physics analysis by the investigators. The article was theoretical, with no participant recorded executing the step. The step was divided into four phases: approach, take-off, flight, and landing. The authors suggested the following: (1) the flight phase has no net body rotation component; (2) there is an illusion of floating created by the changing configuration of arms and legs; (3) if time is taken to slow the landing phase, injury can be prevented; and (4) knowledge of physics can assist dancers in executing elevation steps in a more controlled and expressive manner.

Voloshin, Beijjani, Halpern, and Frankel (1989)[39] investigated the effects of dynamic loading on the musculoskeletal system and the influence of viscoelastic insoles in the shoes of flamenco dancers. Data were collected with two lightweight skin-mounted unidirectional accelerometers. Participants were three female professional flamenco dancers who performed a series of common flamenco dance steps, once using standard flamenco shoes and then with the same shoes with viscoelastic insoles. In assessing the differences in dynamic loading with and without the insoles, flamenco dance produced three times the shock levels as normal walking. Additionally, there was considerable variability between dancers, but there was still a noted reduction in shock impact with the insoles in the shoes, which may potentially reduce long-term problems in flamenco dancers such as degenerative musculoskeletal changes and urogenital disorders.

1990s: Examining Additional Elements: Momentum, Forces, Motor Strategies, Interventions

McNitt-Gray, Koff, and Hall (1992)[59] compared dancers of varying levels performing two types of jumps, examining foot position and its effects on landing mechanics. Data were collected using a one-camera Peak Performance motion analysis system and a forceplate. Participants were six professional modern dancers, six college dance students, and six nondancers, and they performed three trials of each of two conditions: two-foot landings in first position parallel and first position turned out. Trial order was randomized. The participant's preferred trial in each condition was selected for analysis using ANOVA. Dancers and dance students used significantly greater hip and knee flexion than nondancers. Regardless of level, all participants used similar ankle dorsiflexion, but the professional dancers and dance students used a greater range of dorsiflexion throughout the movement, suggesting that plantar flexion was significantly greater for these two groups than the nondancers. Despite differences in kinematics, there were no significant differences in impact peak magnitudes or foot position in landings. There were also no significant differences in landing mechanics between parallel and turned out positions.

Midgett, O'Bryant, Stone, and Johnson (1993)[37] examined the use of arms during the *grand jeté* to extend time spent in the air. Data were collected with a Panasonic video camera and markers placed at the hip and knee joints. Participants were 11 female advanced university dance majors. They performed three trials each of three different arm styles during the *jeté* in random order. Two of the arm styles were from traditional ballet teaching and the third was designed based on physical principles of movement. Three university instructors selected the trials that best approximated set criteria, and these trials were analyzed using ANOVA and orthogonal contrasts when there was significance. There was a significant difference in the amount of time the head spent in the top one fourth of the leap; i.e., the third method allowed the head to stay in the top one fourth of the leap significantly longer, even though the center of mass continued on a parabolic path.

Rasmussen and Hay (1993)[38] were also interested in examining the extent to which the dancer "hangs" or "suspends" in the air during elevation work. Data were collected using a one-camera Peak Performance motion analysis system and markers placed on 21 body landmarks. The participant was one female advanced ballet student who performed four types of leaps: *grand jeté, jeté développé, sissonne fermée*, and a split leap. A series of trials were recorded, and the best trial for each condition was used for analysis, done by calculating time spent in the air for various body segments. "Hang time" was defined as the time that the center of gravity for the whole body followed a parabolic path but the center of gravity for the head, neck, and trunk stayed on a plateau. Results indicated that the "hang time" of the four jumps varied: it was longest for the *jeté développé*, followed by the *grand jeté*. "Hang time" for the *sissonne fermée* was only slightly less. The split leap had poor "hang time," which the researchers suggested was due to her poor timing of raising and lowering the legs. In general, in this study the contribution of the arms to jump height was negligible compared to the contribution of the trunk and legs. Finally, the researchers stated that traditional ballet technique conflicts with optimal strategies for achieving the illusion of suspension in elevation work.

The dissertation research by Murgia (1995)[60] examined biomechanical variables for three types of elevation steps: the stag leap, *grand jeté*, and the jazz leap, also known as a scissor leap. Data were collected using a four-camera Expert Vision Motion Analysis system with markers on multiple body landmarks and a forceplate. Participants were 15 female university and professional dancers and gymnasts with varying levels of training in ballet, modern, and jazz. Participants performed five trials in each of the three conditions in randomized order. Analysis included ANOVA, post hoc tests, Pearson product-moment correlation, and *t*-tests. There were no significant differences between the leaps in takeoff velocity, angle of takeoff, depth and time of *jeté* preparation, magnitude and angle of application of ground reaction force, and range of motion for the hip, knee, and ankle of the takeoff leg. The same take-off preparation was essentially required for all three leaps. The following significant differences were reported: (1) knee peak angular velocity for the stag leap and the *grand jeté* were greater than for the jazz leap; (2) elevation (maximum height) of the jazz leap was greater than the maximum height of the *grand jeté* and stag leap; and (3) time in the air for the stag leap was greater than for the *grand jeté* and jazz leap.

Johnstone, Bauer, and McAuliffe (1996)[74] investigated torque variations at the knee of malaligned Highland dancers doing a six-step Highland fling. Data were collected with the Peak Performance motion analysis system and a forceplate. Participants were seven Highland dancers who performed 10 hops from the beginning of the dance and 10 hops from the end of the dance, to compare changes in knee torque from early to late stages of the dance. A single-subject baseline design was used to analyze the data. All seven participants demonstrated increased knee malalignment and a decrease in knee flexion from early to late stages. The researchers suggest that fatigue may be a factor in these results, with fatigue causing a diminished use of knee flexion, less shock absorbency, and hence increased malalignment.

Simpson, Jameson, and Odum (1996)[77] wanted to determine how jump distance correlates to patellofemoral pressures. Data were collected using a Lo Cam camera with right-side view, markers on the right side of the body, and forceplates. Instead of using EMG electrodes to calculate muscle use, the researchers used a specialized system to determine muscle force called an inverse dynamics model. Participants were six female modern dancers with a minimum of 1 year of training, selected by their instructor for jumping ability. Participants first performed 10 jumps in each of three conditions (30%, 60%, and 90% of the participant's maximum jump distance), followed by 10 trials in a range of jump distances, maintaining balance at the end of the landing, used for analysis. Analysis consisted of ANOVA and Scheffé post hoc analysis, plus equations for determining linear velocities and accelerations. Results showed that as the distance increased, peak patellar pressures increased, knee flexion increased, and time to these events decreased, i.e., velocity increased.

Simpson and Kanter (1997)[78] reported on part 1 of a study examining the effect of jump distance on ankle and knee joint axial forces. Data collection was similar to the preceding study.[77] Six skilled female modern dancers performed 10 trials in each of three conditions (30%, 60%, and 90% of the participant's maximum jump distance), followed by 15 trials in a range of jump distances, maintaining balance at the end of the landing, used for analysis. Multiple calculations and formulas were computed to estimate several parameters, and then qualitative assessments were performed. Several outcomes were observed, including the following: (1) increased jump distance was correlated to greater ground reaction force maxima, greater knee flexion, greater knee and ankle flexion velocity, and greater tibial landing angle; and (2) muscle axial forces have a greater impact than other forces on the magnitude and rate of applying compressive forces at the knee and ankle joints. These high rates of axial forces during large jump distances could be responsible for excessive wear on the joints of the lower extremities.

Simpson and Pettit (1997)[79] reported on part 2 of the same study. Results indicated the following: (1) increased jump distance was correlated to greater knee and ankle joint reaction shear forces and greater quadriceps shear forces; (2) increases in ankle joint shear forces occurred in all participants with increased jump distance; and (3) increased quadriceps shear forces at greater jump distances correlated to increased knee shear forces for only half of the participants.

Poggini, Losasso, Cerreto, and Cesari (1997)[61] evaluated jumping ability in young ballet dancers before and after training. Data were collected with an electronic apparatus called ERGO JUMP, which has a trigger started by the feet releasing from the platform and stopped at touchdown, thereby timing flight time and height of the center of gravity. Participants were 61 classical ballet students in their first 3 years of training at a professional school, 56 females and 5 males. The dancers performed two types of jumps, one from static position (SJ) and one with a preliminary or preparatory countermove (CMJ). They did a series of jumps that included an SJ, a CMJ, and 10 consecutive jumps on two feet, all done in a natural foot position. The second series included the same jumps, but in turned-out first position. Dancers were pre- and post-tested after a 4-month intervention, consisting of what the authors called a physiotechnique program. Results showed a small improvement in jump height in both natural and externally rotated positions after intervention. Pre-intervention, dancers exhibited a common error called double heel strike, which was corrected post-intervention. The researchers discussed the training attitude that overall aesthetics, posture, and control are valued above absolute jump height. They encouraged the use of springboard training in the dancer's regime.

Laws and Petrie (1999)[92] investigated the use of momentum transfer, particularly from the arms, in enhancing vertical jumps in dance. For data collection, the participants jumped from a 2-inch × 12-inch × 6-foot board rigid at one end and supported on the other end by a force sensor. Participants were seven trained ballet dancers (six female and one male) and one female athlete with no dance experience. They performed a series of jumps in two conditions: one with the arms held at the sides, and one with the arms raised during the push-off phase. Force-time plots were graphed, and jump height was calculated using formulas. Results indicated the following: average height gain using the arms was 26%; older, mature dancers increased magnitude of the push-off phase to increase jump height, while smaller, younger dancers increased the duration of the push-off phase; extended duration of push-off phases contributed more to jump height than increased magnitude; less coordination in the use of the arms resulted in less height increase.

Ravn, Voigt, Simonsen, Alkjaer, Bojsen-Moller, and Klausen (1999)[62] examined the choice of strategy for performing two types of vertical jumps in two populations. Data were collected with one 16-mm camera and reflective markers on various body landmarks, a forceplate, and EMG electrodes on selected muscles of the right leg (soleus, medial gastrocnemius, rectus femoris, vastus lateralis, semitendinosus, adductor magnus, and gluteus maximus). Participants were three professional male ballet dancers and three elite male volleyball players. They performed maximum vertical jumps in three conditions: static preparation or squat jump (SJ), countermovement jump (CMJ), and a jump specific to the participant's area of expertise (ballet or volleyball). Formulas were used to calculate jump heights. Two strategies were identified, sequential or simultaneous. The choice of jump strategy for both SJ and CMJ was individual rather than related to training background. In the SJ, the participants using a sequential strategy demonstrated greater trunk inclination, whereas in the CMJ, no correlation existed between choice of strategy and trunk inclination. For ballet dancers, doing the ballet-specific jump with external rotation produced an unexpected result; the moment about the hip joint was negative for the extension phase. Finally, for the ballet and volleyball specific jumps, ballet dancers used a simultaneous strategy and volleyball players used a sequential strategy.

2000s: Recent Work: Laterality, Gender, Body Composition

Golomer and Féry (2001)[35] compared left- and right-side unilateral maximum vertical jumps in professional ballet dancers. Data collection utilized an electronic system called the Jump Meter which measures jump height. Participants were 10 professional right-footed female ballet dancers, who performed 20 total trials of a maximum vertical one-legged jump, alternating sides. Analysis was done by ANOVA and Scheffé post hoc analysis. There was no significant difference in left and right jump height. There were significant differences between various trials, especially between first and last jumps, showing a short-term learning effect and a warm-up effect. The symmetry of left and right side was attributed to symmetry in training.

Harley, Gibson, Harley, Lambert, Vaughan, and Noakes (2002)[73] compared dancers and physically active nondancers to assess quadriceps strength in relation to EMG activity during isometric and stretch-shortening cycle (SSC) muscle activity. Other physiological characteristics (e.g., body composition and flexibility) were also assessed. Data were collected with EMG electrodes placed on the right rectus femoris, a Kin-Com dynamometer, and a forceplate. Participants were 11 female semiprofessional dancers and 11 matched participants who were participants in various forms of physical activity but had no dance training. Maximum voluntary isometric contractions (MVICs) were collected in order to compare the two groups' use of relative percentages of maximum. Participants performed a variety of tests including maximum knee extensor isometric muscle strength, three types of jumps to determine the SSC (squat jump, counter-movement jump, and drop jump), and the vertical jump. Analysis included *t*-tests and Pearson product-moment correlation. Results included the following: Dancers generated greater quadriceps muscle output than nondancers during jumping trials, but they did not jump significantly higher. When jumping, they used a lower percentage of their rectus femoris MVIC as measured by EMG than did the nondancers. The researchers hypothesize three possible reasons for this outcome: (1) dancers may be sacrificing height for aesthetics, (2) there may be training-induced differences in neuromuscular patterns in the dancers, or (3) there may be differences in the elastic components of the musculo-tendinous tissue between the two groups. The researchers made suggestions for teachers to find ways to address this issue of not using full-strength potential to achieve higher jumps in dancers.

Martin, Kulas, and Schmitz (2005)[76] analyzed the asymmetry of ground reaction forces in dancers landing from a drop jump. Data were collected using two forceplates. Twenty college female dancers performed drop jumps at a height of 60 cm in three landing conditions: preferred, soft, and stiff techniques. The participants always began with their preferred landing and led off the box with the right leg. Number of trials was not specified in this abstract. Analysis consisted of repeated measures ANOVA. Results indicated that mean maximum vertical ground reaction force was significantly higher for the right leg for each condition. Mean time to peak vertical ground reaction force was significantly less for the right leg for each condition. The researchers suggested that any research examining jumps and ground reaction force need to use two forceplates, as the forces experienced by the two legs may be different.

Mayers, Agraharasamakulam, Ojofeitimi, and Bronner (2005)[36] investigated musculoskeletal stresses experienced in tap dance. Data were collected with a five-camera Vicon motion analysis system with 39 reflective markers and a forceplate. Six professional tap dancers executed four tap sequences: flaps, cramprolls, pullbacks, and the participant's choice. Each step was repeated four to eight times. Analysis consisted of *t*-tests. Because there were no gender differences, results for all participants were merged for analysis. Landing forces in the vertical plane were lower for tap dance than results reported for other dance forms, which may account for the lower incidence of injury in professional tap dancers than other forms. The researchers suggested that it would be useful to analyze individual joint forces in tap dancers.

Chockley (2007)[70] compared ground reaction forces when landing on the full foot and when landing on full *pointe* in elevation work. Data collection included a Spica Technology motion capture system and a forceplate. In this abstract, no details were given about marker number or placement. Two female dancers performed three trials of jumps, rolling through the whole foot during landing, and three trials landing *en pointe*. Data were analyzed using inverse dynamics to find joint reaction forces in lower extremity joints. Results indicated that landing *en pointe* generated 65.3% of the force that landing on the whole foot did. One reason suggested for this result was the difference in jump height, which was greatly decreased in the *pointe* condition, due to restricted ankle motion.

Orishimo, Kremenic, Pappas, Hagins, and Liederbach (2009)[53] compared drop landing biomechanics in male and female dancers. Data were collected with an eight-camera Eagle motion analysis system using 20 reflective markers and a forceplate. Participants were 33 professional ballet and modern dancers, 12 men and 21 women. Participants performed three single-leg drop landings from a 30-cm platform, landing on the dominant leg on the forceplate. For analysis, the mean values of all three trials were calculated, and two separate multivariate ANOVA (kinetics and kinematics) were performed, followed by *t*-tests. Results demonstrated no gender differences with both males and females using good lower extremity alignment in the landing and a hip-dominant strategy. There was a significant difference between the age at which the dancers began training and the peak hip adduction angle during landing. The researchers suggested that previous research showing gender differences may have been using less experienced dancers.

Falls

Mangelsdorf (1976),[7] as cited in Lessard,[6(pp17-19)] presents the only study in the literature examining falls. This thesis work compared the Swedish fall, the front slide fall, and the forward straight fall, looking at alignment, angle of body at impact, hand placement on floor, and actions of the arms. Data were collected with two 16-mm Bell & Howell motion picture cameras, with white markers placed on black clothing to locate body landmarks. Both frontal and sagittal views were filmed. Participants were one dance faculty member and three advanced university dancers, who performed three trials of each of the three falls in random order. The best trials were selected, and a Recordak Film reader and a Vanguard Motion Analyzer were used for analysis. Results indicated the following conclusions: (1) initial body positions varied between participants, but the final positions were similar for all four dancers; (2) the hands were placed similarly for all participants; (3) for the Swedish fall, there were larger angles of the trunk on impact and greater hyperextension of the hip of the gesture leg; and (4) for the front sliding fall, there were larger angles of the trunk on impact which allowed for a smooth forward slide on contact with the floor.

Motor Strategies

In a theoretical article, Laws (1985)[93] discussed the use of the barre in dance training. This was not a research study and had no participants and no experimental protocol, but the topic is relevant to this review because of the number of research studies examining this issue. Some of Laws' observations include the following: (1) at the barre, more forward shift of torso is possible in performing *arabesque* than may be possible in center work; (2) the barre allows for stabilization of the torso in movements such as *rond de jambe*, which may require internal stabilization techniques in center; (3) turn initiations using the barre cannot be executed in center work in the same manner; and (4) in summary, the barre has important uses but some of the ways it is currently used may not be transferable to work without a barre.

Chatfield (1993/94)[94] examined EMG activity in dancers, comparing isokinetic work to dance movements. Data were collected with EMG electrodes placed on the rectus femoris, biceps femoris, tibialis anterior, and lateral gastrocnemius. A Cybex dynamometer was used for muscle testing. Participants were seven collegiate advanced dancers. With the Cybex, the muscles were tested at various speeds and positions most commonly reported in the dance literature. The dance movements tested were four sequences: a *plié/relevé* sequence; a *développé* sequence front, side, and back; a *grand battement* sequence front, side, and back; and a jumping sequence. Continuous strip chart recordings were produced from the data, and relative values were used to compute group means. Results demonstrated that dancers showed higher levels of muscle activity in dance movements than in the isokinetic testing with the Cybex. Chatfield suggested possible reasons for this outcome and stated that isokinetic testing may be limited in its uses for dance research, particularly when investigating simultaneous muscle function at multiple joints and stabilization functions of muscles in complex movement. Finally, he suggested that research include kinetic and kinematic measures, in addition to EMG data collection, to provide a full view of the complexity of neuromuscular demands in dance.

Chatfield, Barr, Sveistrup, and Woollacott (1996)[54] conducted two studies designed to examine movement repatterning in dance. In study 1, data were collected with EMG electrodes placed on the pectoralis major, rectus femoris, and rectus abdominus. Participants were three collegiate dancers who executed a simple whole body movement, an abdominal contraction resulting in spine flexion with accompanying limb movements, in two conditions, supine and standing on a one-legged balance. Participants did three trials in each condition, received coaching by a certified movement analyst, and then repeated the trials. Analysis consisted of within-subjects $3 \times 3 \times 4$ (subjects by trials by conditions) ANOVA. There was a significant interaction between subjects and conditions, though the researchers stated that this interaction may have masked training effects. The researchers concluded that it was necessary to examine outcomes for individuals, not groups, to understand the data, and a descriptive discussion of each participant's results followed. There were different results for the standing versus supine condition, suggesting that the issue of transfer of training from one context to another needs further investigation.

In study 2, dancers were compared with nondancers in a similar movement task.[54] Data were collected with EMG electrodes placed on the midpoint between umbilicus and pubis symphysis, and kinematic data were collected with a two-camera Watsmart motion analysis system, with markers on the wrist and ankle. Participants were four female advanced collegiate dancers and five female nondancers. All participants received four 90-minute training sessions with a certified movement analyst over a 2-week period. Analysis was a mixed within-subjects 2 × 5 (groups by trials) ANOVA. There was a significant difference between group means. Results included the following: (1) the dancers were highly consistent in the centrally initiated movement used in this study, and (2) the dancers were better than the nondancers at achieving the task, even though the nondancers received training.

Laws (1998)[96] wrote a theoretical article discussing the transfer of linear and rotational momentum in dance movements, such as vertical jumps, *pirouettes*, *fouetté* turns, finger turns, and whip turns. Each jump or turn was described and analyzed using physics principles and formulas. Some of the observations included: (1) the use of arms could increase vertical jump height by 25%; (2) the rate of turn for the *pirouette* was maximized if the arms were kept close to the body and a "windup" preparation was allowed; and (3) for the *fouetté* turn, the gesture leg should reach maximum abduction and external rotation to produce the best momentum for the turn.

Although most of Laws' article[96] was biomechanical analysis, one pilot study was described. A system was constructed to simulate a partner in a finger turn, with a force sensor substituting for the partner's hand. One dancer executed the turn with four different accelerating techniques. The study indicated that the technique that resulted in the maximum turning momentum was consistent with what is considered to be "correct" technique, i.e., the leg extended to *croissé devant*, then moved fully to the side, and then moved to the *pirouette* position. Laws concluded that the appropriate use of momentum can yield the most efficient technique if principles of physics are understood and applied.

Chatfield (2003)[95] discussed the use of EMG and kinematic tools, and how variability in data can be handled and analyzed. This article did not describe a particular research study, but rather serves as a theoretical work, lending insight into ways of viewing and dealing with data variability. Chatfield described variability in two instances: (1) within a single participant's repeated execution of the same task, and (2) between participants. After reviewing several studies in the dance literature, he discussed how variability could be seen as an indicator of motor learning and could provide valuable information to the researcher and educator, by tracking training changes over time or by differentiating between experts and beginners.

Liederbach, Dilgen, Daugherty, Richardson, and Rosen (2003)[75] compared end-range strength in knee flexion of normal knees versus knees with anterior cruciate ligament (ACL) reconstruction, either with semitendinosus/gracilis grafts or patellar tendon grafts. In this conference abstract, minimal information was provided. Data were collected with motion analysis and strength testing equipment. Participants were 60 female and 60 male dancers. Tests included a single-leg stance, dual- and single-leg jump landing, and manual muscle testing of end-range, eccentric hamstring strength. Participants with semitendinosus/gracilis grafts and with patellar tendon grafts were compared to participants in the normal (no ACL reconstruction) group. Additionally, participants' knees with ACL reconstruction were compared to the ipsilateral normal knee. Unfortunately, at the time this abstract was submitted, no results were reported, and to date, the study has not been presented in the literature.

DISCUSSION

Overview

A total of 89 papers are reviewed in this article: 12.35% (n = 11) are theses or dissertations, 18% (16) are conference abstracts, and the remaining 69.65% (62) are articles published in peer-reviewed journals or conference proceedings. It is hoped that many of the conference abstracts covered in this review will eventually be published in journals so that a fuller understanding of the work can be represented.

There is a clear trend toward an increased number of studies reaching the dance science readership over the past four decades. For the 89 articles in this review, 10% (n = 9) are from the 1970s, 18% (16) from the 1980s, 29% (26) from the 1990s, and 43% (38) from 2000 to 2009. It should be noted that 4 of the graduate studies were in the 1970s, 5 in the 1980s, and 2 in the 1990s. This may indicate that dance science studies at the graduate level have moved away from biomechanics tools, or more likely, that more graduate students publish their thesis and dissertation work in peer-reviewed journals after graduation.

Broken down by movement topic, 9.0% (n = 8) explored alignment issues, 9.0% (8) examined *demi plié* and/or *grand plié*, 9.0% (8) examined *relevé*, 3.4% (3) investigated *passé*, 3.4% (3) investigated *degagé*, 7.9% (7) examined *développé*, 3.4% (3) assessed *rond de jambe*, 4.5% (4) analyzed *grand battement*, 1.1% (1) described movement of the arms, 3.4% (3) assessed forward stepping, 6.7% (6) evaluated turns, 31.5% (28) investigated elevation steps, 1.1% (1) assessed falls, and 6.7% (6) described motor strategies. Although there is some overlap in these categories, each article was placed in the movement category that best described its main focus.

The overwhelming number of studies devoted to elevation work is worthy of mention. This fascination with elevation work crosses all four decades and has been examined across genre, age groups, and technical levels. What drives this intense interest in one aspect of dance vocabulary? It may be due to the high impact forces involved and the potential for career ending injuries. Possibly, it is related to the distinct beginning and end to elevation movements, allowing for clarity in data collection. Or it may reflect the extensive number of descriptions in the pedagogy literature for correct execution of these steps and a desire to test these theoretical models.

Another question that can be posed in this context is the following: Research suggests that *grand plié* is not simply a deepening of the *demi plié* in terms of muscle activation and that the rise to full *pointe* is not simply a continuation of the *relevé*. This raises the issue of the relationship of *plié* and *relevé* to jumping mechanisms. Motor control theory tells us that *plié/relevé* and jumping are different motor strategies, but no research to date has examined the difference in these two movement conditions in terms of muscle activation. No one has yet investigated whether dancers use the same muscles in both activities to differing degrees and speeds or if there are different organizations of muscles employed to leave the ground.

Measurement Tools

Regarding measurement tools, 9.0% (n = 8) used photography, 21.3% (19) used some method of filming, 9% (8) used video, 39.3% (35) used motion analysis systems (Elite, Peak, Watsmart, Expert Vision, Ariel, Vicon, Hires, Spica, Eagle), 23.6% (21) collected EMG data, 24.7% (22) used one or more forceplates, and 10.1% (9) used some other data collection apparatus. Six articles were entirely theoretical and did not use any measurement tools. The total adds up to more than 89 articles, as many studies used multiple data collection tools.

There is a clear shift in the literature from the use of cinematography to the use of motion analysis technology. The early studies in the 1970s and 1980s used photography and motion picture film cameras, and tracing techniques, to collect and analyze data. Standing out as an exception to this pattern is the work by Woodruff (1984),[20] who used motion analysis equipment in her examination of the *plié*. Motion analysis did not reappear in the literature for 8 years, with the 1992 study by Mouchnino et al.[46] Perhaps this speaks to the limited access dance researchers, in the early years of dance science exploration, had to the technology that existed and was already in use in biomechanics labs and science-based departments. By the mid-1990s and later, use of motion analysis was in much broader use, and the benefits to the dance field are immeasurable. Kinematics has provided educators and clinicians with insights into the movement strategies of dancers and differences between novice and elite dancers that previously would have been unavailable. There are, however, certain key themes that recur regardless of the tools, and these are discussed in the next section of the discussion.

The use of electromyography (EMG) in dance analysis is both complex and confusing. In the articles examined in this review, 21 reported EMG data collection, but less than half of these used some system of determining maximum voluntary contractions (MVCs) or maximum voluntary isometric contractions (MVICs) for the participants.[15,18,19,26,44,67,73,77–79] In contrast, in the sports research, establishing MVCs or MVICs is the norm. Without a method of determining maximums, the researcher can describe onsets of muscle activation under investigation and compare timing across individual trials or groups of participants, but not amplitudes. For certain researchers, given their research questions, this strategy is sufficient. For other research designs, it would have provided additional insight to have had the potential to examine muscle amplitudes and describe how various groups of dancers might differ in muscle use for a given dance task.

Most likely what inhibits dance researchers from taking this step is the difficulty of collecting MVC data and the lack of consensus surrounding this topic. Questions arise as to the benefits of using MVCs or MVICs for data collection—i.e., whether the collections should be done in isotonic or isometric conditions. It is not yet clear if these tests give a clear picture of dancers. Some dance researchers have no access to complex isokinetic equipment, such as Cybex and Biodex, even if they wanted to collect these data. It would be useful to know if there are systems that do not include large, cumbersome apparatus that dance researchers can use, or if there are other methods, such as percentage of dynamic maximum[26] or inverse dynamics model,[77–79] that have been tested for reliability that dancer researchers can use. It is not only dance research that is struggling with design aspects of dealing with EMG data collection, and as the sophistication of the equipment improves, better research methods need to evolve for biomechanics study using EMGs in all movement fields.

It is unusual to see a dance study that uses forceplates alone as a measurement tool. Of the 22 studies using forceplates, only 2 used this technology exclusively.[68,76] It is clear that dance researchers use forceplates to augment or enhance kinematic and EMG studies, and as such, these data provide valuable additional information. There may be ways that dance researchers can expand their use of forceplate data in describing dance movement (and in furthering the knowledge of ground reaction forces, in particular) and how these might correlate to dance injuries.

Themes

It is not the purpose of this discussion to review or summarize all of the results from the 89 articles included. There are some recurring themes, however, that deserve mention.

First, it should come as no surprise that in almost every study included in this review, elite dancers demonstrate different motor strategies than novices or nondancers and that these differences are judged as superior. Elite dancers' muscle use is efficient, their coordination is smooth and aesthetically pleasing, their balancing strategies are effective, and overall they have higher skill sets. In the occasional study in which the elite dancers do not surpass the nondancers, the researchers usually stated that the dancers were sacrificing one movement aspect (e.g., jump height) for enhanced aesthetics. The intervention studies were not as universally consistent, however, and it is not clear why many of these studies failed to yield positive or significant results. Perhaps the subject sizes were too small or the time periods of the interventions too short to show differences, particularly with elite participants who tend to make small changes in any context. Or it may be that the interventions were simply poorly designed.

A second repeating theme is the conclusion that dancers perform differently when using a barre as opposed to executing the same movement without a barre, both in terms of muscle activation patterns and weight shift strategies. This research goes as far back as the late 1970s and continues up to recent articles. However, the researchers raised several questions that are yet to be answered. Some claimed that there may be ways to use the barre that eliminate this difference. Others wondered if there is a point of negative transfer of training, i.e., if it can be determined how much time at the barre is too much time. This also raises the issue of the implications for additional transfer of training issues; for example, there may be similar differences in strategies when dancers begin moving through space. Few studies have tried to record EMG and kinematic data on dancers moving through space in traveling material, but this may be the next obvious area of exploration.

Another recurring theme is the individual variability of participants within a certain pool. It has been observed that individual dancers are more consistent across multiple trials of the same task than novices or nondancers. Furthermore, when grouped, elite dancers demonstrate more consistent data than groups of novices or nondancers in many of the studies reviewed. Nevertheless, there is considerable variability among participants, even when matched in terms of background, years of training, body type, and other variables. Each individual has a unique way of moving and selecting motor strategies.

Finally, many studies in this review compared current dance pedagogy to efficient movement biomechanics. In several of the studies looking at biomechanics, it is not uncommon for the researchers to conclude that dance teachers recommend methods of achieving movement skills that are inconsistent with optimal biomechanical function. For example, Buchman (1974)[4] compared the Vaganova literature's description[100] of turning elevation steps to elite dancers and found that biomechanically it is essential for the rotary component of a turning elevation step to begin at the moment of take off. However, the Vaganova literature instructs teachers to cue dancers to elevate first, and then add the rotation at the top of the jump. Laws and Lee (1989)[90] stated that a *jeté* is less effective and has less height if the turnout of the push-off foot is maintained during the take-off phase; they asserted, however, that teachers consistently instruct dancers to maintain their full turnout in both legs during all phases of the *jeté*. In another analysis, Laws (1998)[96] suggested that the rate of turn for the *pirouette* is maximized if the arms are kept close to the body and a "wind-up" preparation is allowed, and yet he states that few teachers allow a "wind-up" preparation for classical turns. He suggested that perhaps sacrifices are made with regard to optimal biomechanics to satisfy aesthetic demands, but it would certainly be of value to question some of these inconsistencies.

Additionally, there are contradictions between what dance pedagogy recommends and the movement strategies employed by elite dancers. Ryman (1978)[14] and Dozzi (1989)[34] both found several aspects of jumping techniques in elite dancers that they stated contradict common teaching instructions for these dance movements. Examples include using the deepest possible *plié* to attain higher jumps when moderate *pliés* yield the highest elevation, and pressing the heels into the floor on landings as the best technical strategy, which actually encourages the double-heel strike. Similarly, studies of leg gestures involving large range of motion[15,28,29,50,84] reported significant pelvic tilt in elite dancers, and yet the pedagogy literature recommends that teachers should instruct dancers to keep the pelvis still in many of these gestures, including *grand battement devant* and *à la seconde*.[97–100] Perhaps this cue is an effective "image" to reduce unnecessary compensations. Possibly, the elite dancers are executing the movement incorrectly, or at least lacking optimal efficiency. Or perhaps it is simply ineffective pedagogy, and teachers might improve pedagogical strategies by examining traditional practice.

Research Design

In the 89 articles in this review, 6 were theoretical discussions and had no research participants. In the remaining 83 studies, 22.9% (19) had 5 or fewer participants, while 43.4% (36) had 10 or fewer participants. There is an increasing interest in single-subject design and within-subject design, in which multiple trials are collected for a single participant or for a few participants. The argument in favor of this approach is based on the earlier observation of high variability among individual participants, and collapsing data into groups may mask information that is crucial to a full understanding of the movement being studied. However, the literature on single-subject design suggests that this method of research is appropriate for determining variability when using intervention protocols, where there are repeated data collections of a participant first as baseline and then periodically to measure the effect of the intervention.[101]

"Snapshot" single-subject studies in which data are collected one time to assess a participant's motor strategies are of questionable value. If in fact there is such high variability between individual dancers, what can be learned from a study of this design? Generalizing results to a larger pool would be at best hypothetical, but it might serve as a pilot study for a projected larger study. Perhaps what might produce the best of both designs is to collect data on larger numbers, examine and describe individual data thoroughly, and then proceed to collapse individual data sets into group data for analysis.

In conclusion, it is crucial that the dance community understand how to make use of the research unfolding in the biomechanics labs. It seems that there is currently a gap between the research data being published and the evolution of pedagogy and practice. Beyond finding ways to increase communication between researchers and practitioners through conferences and publications, there is a need for interpreters of the information, for those people who live in both worlds to relay practical implementation strategies of new information into the educational environment.

REFERENCES

1. Koutedakis Y. Biomechanics in dance. J Dance Med Sci 2008;12(3): 73–74.
2. Kneeland JA. Dancer prepares (series of 4 articles). Dance Magazine 1966; 4(Mar–Jun):49–51,57–59,65–67,67–69.
3. Bannister JK. Investigation of the interrelationships of the pelvic angle, lumbar angle, hip mobility and low back pain of college students majoring in dance [thesis]. Eugene, OR, University of Oregon, 1977.

4. Buchman SD. A cinematographic analysis of the grand jeté [master's thesis]. Denton, TX, Texas Women's University, 1974.
5. Gaffney SD. A cinematographic analysis of the straight leg leap (grand jeté) [master's thesis]. Denton, TX, Texas Woman's University, 1974.
6. Lessard VC. Biomechanical analysis of the classical grand plié and two stylistic variations [dissertation]. Denton, TX, Texas Woman's University, 1980.
7. Mangelsdorf S. Three forward falls in dance: a cinematographic analysis [master's thesis]. Denton, TX, Texas Woman's University, 1976. (as cited in Lessard,6 1980, pp17–19.)
8. McMillan MH. A cinematographic analysis of characteristic likenesses and differences between skilled, semi-skilled, and non-skilled performances of pirouettes [master's thesis]. Denton, TX, Texas Women's University, Denton, 1972.
9. Minton SC. The effects of several types of teaching cues on postural alignment of beginning modem dancers: a cinematographic analysis [dissertation]. Denton, TX, Texas Woman's University, 1981.
10. Shea MM. A kinematic and descriptive study of the rotation of the major body parts in the performance of the fouetté sauté [master's thesis]. Madison, WI: University of Wisconsin, 1981.
11. Hinson M, Buckman S, Tate J, Sherrill C. The grand jeté en tournant entrelacé (tour jeté): an analysis through motion photography. Dance Res J 1978;10/1:9–13.
12. Laws KL. An analysis of turns. Dance Res J 1978–79;11/1–2:12–19.
13. Nichols L. Structure in motion: the influence of morphology, experience, and the ballet barre on verticality of alignment in the performance of the plié. In Taplin DT (ed): New Directions in Dance. Toronto, Pergamon Press, 1979, pp147–157.
14. Ryman R. Kinematic analysis of selected grand allegro jumps. In Woodruff D (ed): 5th CORD Conference, Congress on Research in Dance. New York, Congress on Research in Dance, 1978, pp231–242.
15. Ryman R, Ranney D. A preliminary investigation of two variations of the grand battement devant. Dance Res J 1978/79;11(1/2):2–11.
16. Woodhull-McNeal AP, Clarkson PM, James R, Watkins A, Barrett S. How linear is dancers' posture? Med Probl Perform Art 1990;5(4): 151–154.
17. Barnes MA, Krasnow D, Tupling SJ, Thomas M. Knee rotation in classical dancers during the grand plié. Med Probl Perform Art 2000;15:140–147.
18. Trepman E, Gellman RE, Solomon R, Murthy KR, Micheli LJ, De Luca CJ. Electromyographic analysis standing posture and demi-plié in ballet and modern dancers. Med Sci Sports Exerc 1994;26/6: 771–782.
19. Trepman E, Gellman RE, Micheli LJ, De Luca CJ. Electromyographic analysis of grand-plié in ballet and modern dancers. Med Sci Sports Exerc 1998;30/12:1708–1720.
20. Woodruff J. Plies—some food for thought. Kinesiol Med Dance 1984;7(l):8–9.
21. De Bartolomeo O, Sette MM, Sloten JV, Albisetti W. Electromyographic study on the biomechanics of the lower limb during the execution of technical fundamentals of dance: the releve [poster]. J Biomechan 2007;40/2:S789.
22. Kadel N, Donaldson-Fletcher EA, Segal A, Falicov A, Orendurff M. Kinematic, kinetic, and electromyographic (EMG) analysis of muscle activity during rise to the pointe position. In: Solomon R, Solomon J (eds): Proceedings of the 14th Annual Meeting of the International Association for Dance Medicine and Science. San Francisco, CA, IADMS, 2004, pp244–247.
23. Lin C-F, Su F-C, Wu H-W. Ankle biomechanics of ballet dancers in relevé en pointe dance. Res Sports Med 2005;13(1):23–35.
24. Massó N, Germán A, Rey F, Costa LL, Romero D, Guitart S. Study of muscle activity during relevé in first and sixth positions. J Dance Med Sci 2004;8(4):101–107.
25. Bronner S, Brownstein B. A kinematic analysis of the passé in skilled dancers [abstract]. J Dance Med Sci 1998;2(4)149.
26. Lepelley MC, Thullier F, Koral J, Lestienne FG. Muscle coordination in complex movements during jete in skilled ballet dancers. Exp Brain Res 2006;175/2:321–331.
27. Feipel V, Dalenne S, Dugailly P-M, Salvia P, Rooze M. Kinematics of the lumbar spine during classic ballet postures. Med Probl Perform Art 2004;19(4):174–180.
28. Kwon Y-H, Wilson M, Ryu J-H. Analysis of the hip joint moments in grand rond de jambe en l'air. J Dance Med Sci 2007;11(3):93–99.
29. Bosco Calvo J, Iacopini E, Pellico L. The spine and pelvis during grand battement: a 3-D video study [abstract]. In Solomon R, Solomon J (eds): Proceedings of the 14th Annual Meeting of the International Association for Dance Medicine and Science. San Francisco, CA, IADMS, 2004, p221.
30. Wang A-T, Huang C-C, Hsieh C-C, Hu C-C, Lu T-W. Electromyography analysis of grand battement in Chinese dance [translation]. In Lim CT, Goh JCH (eds): Proceedings of the 13th International Conference on Biomedical Engineering. Singapore, IFMBE, 2008, pp 2064–2067.
31. Kuno-Mizumura M, Seta A, Mizumura S. Biomechanical characteristics of arm movements by skilled dancers in 'Swan Lake.' In Solomon R, Solomon J (eds): Proceedings of the 14th Annual Meeting of the International Association for Dance Medicine and Science. San Francisco, CA, IADMS, 2004, pp296–298.
32. Laws K. The mechanics of the fouetté turn. Kinesiol Dance. 1986;28(4):22–24.
33. Laws K, Fulkerson L. The slowing of pirouettes. Kinesiol Med Dance 1992/1993;15(1 Fall/Win):72–80.
34. Dozzi PA. A computer-assisted investigation into the effects of heel contact in ballet allegros. In JA Gray (ed): Dance Technology: Current Applications and Future Trends. Reston, VA, American Alliance for Health, Physical Education, Recreation, and Dance, 1989, pp83–91.
35. Golomer E, Féry YA. Unilateral jump behavior in young professional female ballet dancers. Int J Neurosci 2001;381(1–2):31–35.
36. Mayers L, Agraharasamakulam S, Ojofeitimi S, Bronner S. Ground reaction and lower extremity joint forces produced during tap dance. In Solomon R, Solomon J (eds): Proceedings of the 15th Annual Meeting of the International Association for Dance Medicine and Science. Stockholm, Sweden, IADMS, 2005, pp33–38.
37. Midgett VD, O'Bryant HS, Stone MH, Johnson RL. Effects of arm position on hang time during a grand jeté. Kinesiol Med Dance 1993;15(2 Spr/Sum):3–22.
38. Rasmussen CC, Hay JG. The illusion of suspension in selected dance leaps. Kinesiol Med Dance 1993;15(2 Spr/Sum):23–41.
39. Voloshin A, Beijjani F, Halpern M, Frankel V. Dynamic loading on flamenco dancers: a biomechanical study. Hum Mov Sci 1989;8:508–513.
40. Wiley HC. A new model for teaching saut de basque. Dance Res J 1987-88;19/2:9–13.
41. Bronner S, Brownstein B, Worthen, Ames S. Skill acquisition and mastery in performance of a complex dance movement [abstract]. J Dance Med Sci 2000;4(4):138.
42. Chatfield SJ, Krasnow DH, Herman A, Blessing G. A descriptive analysis of kinematic and electromyographic relationships of the core during forward stepping in beginning and expert dancers. J Dance Med Sci 2007;11/3:76–84.
43. Krasnow D, Chatfield SJ, Blessing G. A preliminary investigation of the relationship of alignment and abdominal activity during transfer of weight through space in dancers [abstract]. J Dance Med Sci 2002; 6(1):27.
44. Ferland G, Gardener P, Lèbe-Néron RM. Analysis of the electromyographic profile of the rectus femoris and biceps femoris during the demi-plié in dancers [abstract]. Med Sci Sports Exerc 1983;15:159.
45. Monasterio RA, Chatfield SJ, Jensen JL, Barr S. Postural adjustments for voluntary leg movements in dancers [thesis]. Eugene, OR, University of Oregon, 1994.
46. Mouchnino L, Aurenty R, Massion J, Pedotti A. Coordination between equilibrium and head-trunk orientation during leg movement: a new strategy built up by training. J Neurophysiol 1992; 67/6:1587–1598.
47. Ojofeitimi S, Bronner S, Spriggs J, Brownstein B. Effect of training on postural control and center of pressure displacement during weight shift [abstract]. J Orthop Sports Phys Ther 2003;33(2):A-15.
48. Sandow E, Bronner S, Spriggs J, Bassile CC, Rao AK. A kinematic comparison of a dance movement in expert dancers and novices [abstract]. J Orthop Sports Phys Ther 2003;33(2):A-25.
49. Spriggs J, Bronner S, Brownstein B, Ojofeitimi S. Smoothness during a multi-joint movement: 2D and 3D analysis between groups of differing skill levels [abstract]. In Solomon R, Solomon J (eds): Proceedings of the 11th Annual Meeting of the International Association for Dance Medicine & Science. New York, IADMS, 2002.
50. Wilson M, Lim B-O, Kwon Y-H. A three-dimensional kinematic analysis of grand rond de jambe en l'air, skilled versus novice ballet dancers. J Dance Med Sci 2004;8(4):108–115.
51. Thullier F, Moufti H. Multi-joint coordination in ballet dancers. Neurosci Lett 2004;369/1:80–84.
52. Bronner S, Ojofeitimi S. Gender and limb differences in healthy elite dancers: passé kinematics. J Mot Behav 2006;38(l):71–79.

53. Orishimo KF, Kremenic IJ, Pappas E, Hagins M, Liederbach M. Comparison of landing biomechanics between male and female professional dancers. Am J Sports Med 2009;37:2187–2193.
54. Chatfield SJ, Barr S, Sveistrup H, Woollacott MH. Electromyographic and kinematic analysis of movement repatterning in dance. Impulse Int J Dance Sci Med Educ 1996;4(3):220–234.
55. Gamboian N, Chatfield SJ, Woollacott MH. Further effects of somatic training on pelvic tilt and lumbar lordosis alignment during quiet stance and dynamic dance movement. J Dance Med Sci 2000;4(3):90–98.
56. Couillandre A, Lewton-Brain P, Portero P. Exploring the effects of kinesiological awareness and mental imagery on movement intention in the performance of demi-plié. J Dance Med Sci 2008;12(3): 91–98.
57. Gamboian N, Chatfield SJ, Woollacott MH, Barr S, Klug GA. Effect of dance technique training and somatic training on pelvic tilt and lumbar lordosis alignment during quiet stance and dynamic dance movement. J Dance Med Sci 1999;3(1):5–14.
58. Krasnow DH, Chatfield SJ, Barr S, Jensen JL, Dufek JS. Imagery and conditioning practices for dancers. Dance Res J 1997;29/1:43–64.
59. McNitt-Gray JL, Koff SR, Hall BL. The influence of dance training and foot position on landing mechanics. Med Probl Perform Art 1992; 7/3:87–91.
60. Murgia CJ. Relationships among selected kinetic and kinematic parameters of three types of dance leaps [dissertation]. Eugene, OR, University of Oregon, 1995.
61. Poggini L, Losasso S, Cerreto M, Cesari L. Jump ability in novice ballet dancers before and after training. J Dance Med Sci 1997;1(2):46–50.
62. Ravn S, Voigt M, Simonsen EB, Alkjaer T, Bojsen-Moller F, Klausen K. Choice of jumping strategy in two standard jumps, squat and countermovement jump—effect of training background or inherited preference? Scand J Med Sci Sports 1999;9/4:201–208.
63. Sugano A, Laws K. Physical analysis as a foundation for pirouette training. Med Probl Perform Art 2002;17(1):29–32.
64. Torres-Zavala C, Henriksson J, Henriksson M. The influence of the barre on movement pattern during performance of développé [abstract]. In Solomon R, Solomon J (eds): Proceedings of the 15th Annual Meeting of the International Association for Dance Medicine and Science. Stockholm, Sweden, IADMS, 2005, pp147–148.
65. Wieczorek N, Casebolt JB, Lambert CR, Kwon YH. Resultant joint moments during a dégagé with and without a barre. In Solomon R, Solomon J (eds): Proceedings of the 17th Annual Meeting of the International Association for Dance Medicine & Science. Canberra, Australia, IADMS, 2007, pp318–323.
66. Wilmerding MV, Gurney B, Torres V. The effect of positive heel inclination on posture in young children training in flamenco dance. J Dance Med Sci 2003;7/3:85–90.
67. Wilmerding M, Heyward VH, King M, Fiedler KJ, Stidley CA, Pett SB, Evans B. Electromyographic comparison of the développé devant at barre and centre. J Dance Med Sci 2001;5/3:69–74.
68. Albers D, Hu R, McPoil T, Cornwall MW. Comparison of foot plantar pressures during walking and en pointe. Kinesiol Med Dance 1992/1993;15(1 Fall/Win):25–32.
69. Becker TJ. Kinetic and kinematic parameters of landing impact forces in the dance jump and leap [thesis]. Eugene, OR, University of Oregon, 1985.
70. Chockley C. Ground reaction force comparison between jumps landed on full foot and on pointe [abstract]. J Dance Med Sci 2007;11(1): 23–24.
71. Clippinger-Robertson KS, Hutton RS, Miller DI, Nichols TR. Mechanical and anatomical factors relating to the incidence and etiology of patellofemoral pain in dancers. In CG Shell (ed): The Dancer as Athlete (1984 Olympic Scientific Congress Proceedings, vol 8). Champaign, IL, Human Kinetics, 1986, pp53–72.
72. Dozzi P, Winter D. Biomechanical analysis of the foot during rises to full pointe: implications for injuries to the metatarsal-phalangeal joints and shoe redesign. Kinesiol Med Dance 1993/1994;16(1 Fall/Win): 1–11.
73. Harley YXR, Gibson AS, Harley EH, Lambert MI, Vaughan CL, Noakes TD. Quadriceps strength and jumping efficiency in dancers. J Dance Med Sci 2002;6(3):87–94.
74. Johnstone RJ, Bauer T, McAuliffe J. Knee torque kinetics during Highland dancing. In Bauer T (ed): Proceedings of the XIII International Symposium for Biomechanics in Sport. Thunder Bay, Ontario, Lakehead University, 1996, pp48–51.
75. Liederbach M, Dilgen F, Daugherty J, Richardson M, Rosen J. Comparison of kinetic, kinematic and electromyographic activity and strength in dancers with ACL-normal versus ACL-reconstructed knees [abstract]. J Dance Med Sci 2003:7(2):61.
76. Martin NM, Kulas AS, Schmitz RJ. Asymmetrical landing forces in female dancers [abstract]. J Athl Train 2005;40(2 suppl):S57.
77. Simpson KJ, Jameson EG, Odum S. Estimated patellofemoral compressive forces and contact pressures during dance landings. J Appl Biomech 1996;12(1):1–14.
78. Simpson, KJ, Kanter L. Jump distance of dance landings influencing internal joint forces: I. axial forces. Med Sci Sports Exerc 1997;29(7):916–927.
79. Simpson KJ, Pettit M. Jump distance of dance landings influencing internal joint forces: II. shear forces. Med Sci Sports Exerc 1997;29(7):928–936.
80. Yoshida M, Kuno-Mizumura M. The changes of EMG activity with fatigue during heel-rise test in Japanese female dance students [abstract]. J Dance Med Sci 2003;7(2):66.
81. Brink CG. Dance analysis and high technology. Kinesiol Med Dance 1991/92;14(1 Fall/Win):106–112.
82. Bronner S, Spriggs J. Biomechanical analysis in dance: insight into injury, control and optimization. In Proceedings, 21st Annual Symposium on Medical Problems of Performing Artists. Aspen, CO, Performing Arts Medicine Association, 2003.
83. Minton S. Research in dance: educational and scientific perspectives. Dance Res J 2000;32/1(Sum):110–116.
84. Ranney D. Biomechanics of dance. In Clarkson PM, Skrinar M. Science of Dance Training. Champaign, IL, Human Kinetics Books, 1988, pp125–144.
85. Wilson M, Kwon Y-H. The role of biomechanics in understanding dance movement. J Dance Med Sci 2009;12/3:109–116.
86. Solomon R, Solomon J. Dance Medicine and Science Bibliography, 4th ed. Andover, NJ, J Michael Ryan, 2007.
87. Kadel N, Couillandre A. Kinematic, kinetic, and electromyographic (EMG) analysis comparing unsupported versus supported movements in the 'en pointe' position [abstract]. J Dance Med Sci 2007; 11(1):23.
88. Ahonen J, Hobden R. Biomechanical survey on arabesques and attitude croisée devant and their influence on the hip joint and pelvis in the open and closed kinetic chain [abstract]. J Dance Med Sci 2003; 7(2):64.
89. Meglin J, Woollacott M. The neural choreography underlying a pirouette arabesque. Kinesiol Med Dance 1992;14:95–105.
90. Laws K, Lee K. The grand jeté—a physical analysis. Kinesiol Dance 1989;11(4):12–13.
91. Li L, Laws K. The physical analysis of Da She Yan Tiao. Kinesiol Dance 1989;11(4):9–11.
92. Laws K, Petrie C. Momentum transfer in dance movements—vertical jumps: a research update. Med Probl Perform Art 1999;14(3):138–140.
93. Laws K. The biomechanics of barre use. Kinesiol Dance 1985;7(4):6–7.
94. Chatfield S. Electromyographic response of dancers to isokinetic work and select dance movements. Kinesiol Med Dance 1993/1994;16(1 Fall/Win):60–82.
95. Chatfield S. Variability of electromyographic and kinematic measurement in dance medicine and science research. J Dance Med Sci 2003:7(2):42–48.
96. Laws K. Momentum transfer in dance movement. Med Probl Perform Art 1998;13(4):136–145.
97. Kassing G, Jay DM. Teaching Beginning Ballet Technique. Champaign, IL, Human Kinetics, 1998.
98. Lawson J. Teaching Young Dancers. Brooklyn, NY, Theatre Arts Books, 1984.
99. Minden, EG. The Ballet Companion: A Dancer's Guide to the Technique, Traditions, and Joys of Ballet. New York, Simon & Schuster, 2005.
100. Vaganova A. Basic Principles of Classical Ballet. New York, Dover Books, 1969. (NEW)
101. Barlow DH, Nock MK, Hersen M. Single Case Experimental Designs: Strategies for Studying Behavior Change, 3rd ed. Columbus, OH: Allyn & Bacon, 2008.