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COORDINATION VARIABILITY AND INJURY RISK IN EXPERIENCED COLLEGIATE DANCERS

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ABSTRACT

COORDINATION VARIABILITY AND INJURY RISK IN EXPERIENCED COLLEGIATE DANCERS

By

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Dance is a sport that places a number of physical demands upon the human body, and injuries are a common occurrence in the sport. While it has not yet been linked to dance-related injury, coordination variability (CV) is a measure of how much movement strategy changes between repetitions of a task and low levels of CV have been linked to injury in other sports. This study aimed to determine the relationship between CV and dance injury in collegiate dancers. Eight (8) undergraduate student subjects were recruited from the dance major and minor, BFA major and minor, and recreational dancers who engaged in >3 hours of dance per week. At intake dancers completed 10 trials of a sauté jump task to measure baseline CV using a modified vector coding (MVC) approach. Dancers then completed 4 months of weekly check-in forms to report any and all injuries sustained during the week and number of hours spent dancing. Analysis revealed that in general, non-injured participants tended to have more frequent fluctuations and overall higher CV values than the non-injured group, especially in couplings 1 ($p = 0.052$, effect size 2.31) and 3 ($p = 0.31$, effect size 1.59). Hours per week spent in dance and years of experience did not appear to have any effect on injury status. This study highlighted certain trends which point to a relationship between lower coordination variability and injury in dancers. This research serves as a beneficial study to examine the role of CV in sports injury.

Key words: DYNAMICAL SYSTEMS, LANDING, VECTOR CODING, SAUTÉ JUMP

DEDICATION

This thesis is dedicated to my bean for always encouraging me to do hard things and reminding me about the alpaca farm, and to nubs for being the best dancer on the planet.

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LIST OF SYMBOLS & ABBREVIATIONS

Anterior Cruciate Ligament ....ACL

Anterior Superior Iliac Crest ....ASIS

Coordination Variability CV

Degrees of Freedom ....DOF

Fifth (5^{th}) Lumbar Vertebra L5

First (1^{st}) Sacral Vertebra S1

Northern Michigan University ....NMU

Posterior Superior Iliac Spine ....PSIS

SARS-CoV-2 Pandemic COVID-19

CHAPTER I: JOURNAL MANUSCRIPT

INTRODUCTION

Dance is a sport that places a wide variety of physical demands upon the human body. Underscored by genres such as modern, ballet, jazz, and tap, dance requires a great deal of flexibility, awareness, and coordination to properly perform (1,2). Because of the focus on artistic and aesthetic quality in dance, athletes spend a great deal of time in rehearsal to perfect complicated choreography moves (3). This high training load has been linked to an elevated injury risk in dancers, primarily seen in the lower extremity (2,3). Common lower extremity injuries in dancers include ankle sprains, muscle and ligament strains of the knee and hip, lower back injury, and stress fractures (3-6).

An important concept to consider when discussing injury is coordination, defined as the process of "mastering redundant biomechanical degrees of freedom" (7,8). As injuries are often the product of a complex system of interacting mechanisms within the human body, it becomes necessary to examine how these systems coordinate with one another to create movement strategies. Analysis of movement does not have to be limited to coordination; it is also advantageous to study variability, which gives us information on the flexibility and adaptability of a system. Performance variability, or 'end-point' variability, states that expert athletes should have more stability and therefore less variability than novices (1,9). When it comes to end-product performance in a sport, the goal is to decrease the degrees of freedom in a system and thus decrease the amount of variability in order to constrain the performance to a strict range of movements, as seen in a study by Arutyunyan et al. (10) which showed less 'end point' variability in experienced pistol shooters. Movement variability, on the other hand, refers to the "flexibility or stability of how a task is achieved" (1). Coordination variability is a product of movement variability and is often higher in experienced athletes (8-11). For example, Arutyunyan and colleagues noted expert shooters displayed greater coordination variability in their individual movement strategy than novice shooters (10). It makes sense that experienced athletes would have some flexibility in their coordination patterns and less flexibility in their performance patterns.

In contrast with the above trends, dancers exhibit a different change in coordination variability with increasing skill. Several studies have found that as dance skill increases, coordination variability decreases in comparison with lower-skilled dancers or non-dancers (1,12-14). While the reason for these differing results is not clear, it is possible the aesthetic nature of dance limits coordination variability by requiring dancers to constrain movements more than in other sports in order to be visually consistent. To further illustrate this point, Shih et al. (1) noted a decrease in inter-limb force coordination variability in skilled dancers compared to non-dancers during the transition phase in jumps, indicating better performance by maintaining consistency in jump rate and jump height. Perhaps more in line with findings in other sports, Jarvis et al. (15) noted an increase in coordination variability in the trunk of experienced dancers in comparison to nondancers during the late flight phase of a sauté jump.

A more complex theory proposed by Wilson et al (8) expanded upon these conflicting findings, noting a U-shaped change in coordination variability in track and field triple jumpers, with novice jumpers displaying a high level of coordination variability, intermediate jumpers displaying the lowest coordination variability, and experts displaying a high level of coordination variability. This U-shaped trend observed in complex sports like the triple jump has not been documented in dance, possibly due to a difference in skill development between the sports. The triple jump is an event that emphasizes end-goal performance by measuring distance jumped, which presumably enables a variety of movement strategies during skill development to achieve this end, while dance is a sport that heavily emphasizes the appearance of each move, potentially limiting skill development to a finite number of aesthetically pleasing movements.

As evidenced above, most sports performance benefits from increased coordination variability. The exception to this rule is dance, possibly due to the rigid constraints of maintaining visual appeal. This discrepancy highlights the need to understand more about the relationship between coordination variability, performance, and possible injury risk in dancers.

According to previous literature, lower extremity injuries in experienced dancers have been linked to incorrect take-off and landing strategy (12,16) and unexpected falls (6), but the majority of studies on dance injuries agree overuse and overtraining are the main sources of documented injuries in professional dancers (2,3,12,17,18). Furthermore, several studies have connected coordination variability to overuse and acute injury risk: Pollard et al. (19) highlighted a relationship between decreased coordination variability and the risk of developing acute injuries, and Lipsitz (20) suggested a hypothesis called the “loss of complexity”, which states as coordination variability decreases to a critical point, injury or dysfunction tend to emerge.

Hamill et al. (9) summarized the relationship between coordination variability and injury by observing that the state of higher coordinative variability is a healthier state than one with low coordinative variability, and acknowledged there is most likely an upper limit of ideal coordinative variability when it comes to an athlete’s optimal, injury-free functioning. A perplexing finding in a recent study about running-related overuse injury found an opposite trend: the injured runners exhibited greater knee-ankle and shank-ankle coordinative variability than the non-injured runners, leading to questions about how coordination variability contributes to overuse injury (21). Desai and Gruber's findings highlight the complex and often hard to discern relationship between injury and coordination variability, as it is often task- and task-phase-dependent (21). In addition to examining how coordination variability and overuse influence athletes' risk of injury, other studies have examined specific movements commonly undertaken by dancers to assess how individual movement strategy differs between dancers and non- dancers and how these coordination patterns might influence injury susceptibility over time.

Bipedal and unipedal jumps are some of the most common movements in dance (1,5,12,16,18), as are turns, choreographed falls (6), and squat variations (1). During each of these movements, dancers are required to coordinate their two lower limbs for proper style and to minimize injury (1,14). Coordination variability of the lower limbs can be measured by recording the three-dimensional position of a joint, segment, or limb in space throughout a task or phase of a task, creating angle-angle diagrams of one segment or joint in relation to another, and assessing the motion of both points in relation to one another through vector coding methods (9,11,12,19,21-24). Previous studies have employed this method to investigate a variety of movements including jump tasks (15), which are movements often utilized in dance studies. We can take these methods and the information on coordination variability and injury risk in athletes in other sports and apply it toward assessing the relationship between coordination variability and injury risk in dancers.

As many studies have shown, injury tends to emerge as coordination variability decreases in most athletic populations (9,19,20). However, applying this rule to dance is a little less straightforward. Previous literature indicates that as dance skill increases, coordination variability decreases (1,12-14). In other words, as dancers improve, their coordination variability becomes more limited, potentially making them more vulnerable to injury. Studies have shown injury tends to emerge in the general athletic population with overtraining (2,3,12,17,18), landing from a jump (12,16), and in cases of lower coordination variability (9,19,20). In line with these findings, we would expect to find in dancers a phenomenon similar to what has been recorded in other athletes, with higher coordination variability in the healthy state and lower coordination variability leading to increased risk of injury.

To date, a handful of studies have described injuries in dancers (1-3,5,12,17,18), a few have studied limb coordination and coordination variability in jump tasks and balance (1,14), a few have documented injury incidence in professional dancers over the long term (3,4,25), and several have prospectively studied overuse injury risk in a variety of sports settings (3,21,25,26). To the knowledge of the authors of this paper, no studies have prospectively investigated intra-limb coordination variability as a risk factor for recorded injury incidence in a group of dancers over time. This type of study might highlight how important it is for dance instructors to emphasize limb coordination while modulating movement variability within a desirable range, as well as potentially serving as a screening tool to identify certain dancers at higher risk for injury due to individual movement strategy.

Thus, the aim of this study was to examine trends connecting individual movement strategy and injury incidence in collegiate dancers. In line with what previous literature has found regarding the relationship between coordination variability and injury, we hypothesized we would see lower coordination variability in injured dancers and higher coordination variability in non-injured dancers.

METHODS

All procedures used in this study were approved by the Institutional Review Board at Northern Michigan University. All procedures were conducted in compliance with the approved protocol. Written informed consent was obtained from all participants following a written and verbal description of the study to ensure complete understanding of the procedures. COVID-19 protocol consent was obtained from all subjects in accordance with University policies for human subjects research during the pandemic.

The purpose of this study was to measure the correlation of movement coordination and intra-limb coordination variability with injury incidence across 4 months in a collegiate dance cohort. Utilizing jump-task trials within a 3-D motion capture field to collect kinematic data from the shank, ankle, and foot gave insight into the coordinative structures of the lower limb and how baseline coordination variability and injury risk are related.

Participants: A total of nine (n = 9) dancers were recruited from the Northern Michigan University dance major program, and one (1) withdrew two weeks into the study to make the final number of participants eight (n = 8). The ideal number of participants was 20-30 dancers, according to power analyses and sample size estimates from similar prospective cohort studies (21,27). Eligible dancers met the following criteria: age 18-24, 5+ years of contemporary, ballet, or jazz technique experience, currently an NMU dance major/minor, BFA major/minor, or NMU student who engages in recreational dance for >3 hours per week, availability for the 2021 calendar year, and no current injuries at intake that would impair jumping or dancing tasks. An intake questionnaire assessed participants' amount of dance experience (in years), age, previous injuries, and anthropometric measurements (height and mass). At the initial testing session, participants underwent 3-dimensional motion analysis of a fundamental dance jump, the sauté.

Instrumentation: Kinematic data were collected using a 10-camera system and Cortex Motion Analysis software (Motion Analysis Corporation, Santa Rosa, CA, USA) at a sampling rate of 500Hz. Kinematic data were processed and modeled using Visual 3-DTM (C-Motion Inc., Germantown, USA). Marker histories were smoothed with a fourth-order, low-pass 12Hz Butterworth filter. Microsoft Excel (2016, Microsoft, Redmond, WA, USA) was used to create angle-angle plots and calculate mean coupling angle, coordination, and intra-limb coordination variability from kinematic data.

Protocol: Testing visit protocol was as follows: at intake, participants filled out a questionnaire, received verbal and written descriptions of the nature of the study, and read and signed an informed consent document and a University mandated COVID-19 informed consent document. Participants then completed a 5-minute warm up consisting of their choice of treadmill walking, dynamic stretching, jumping, or range of motion exercises as they normally would warm up for dance class. Each participant was then fitted with a lower extremity retroreflective marker set: one marker placed between L5 and S1 to estimate whole body movement, as described by Shih et al. (1). Markers were also placed at several other anatomical locations on the lower extremity to measure lower limb coordinative structures: pelvis, hip, knee, shank, ankle, and foot. Markers of the pelvis were placed at the anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS); markers of the hip and thigh were placed at the greater trochanter of the femur, mid-thigh, and the lateral and medial epicondyles of the femur; markers of the knee and shank were placed at the tibial tuberosity, mid-shank, medial and lateral malleolus of the ankle; markers of the foot included the head of the 2nd metatarsal, head of the 5th metatarsal, and the posterior surface of the calcaneus (28). Participants then completed a sauté jump from first position with 30 seconds of rest between trials. Participants were instructed to stand upright and place feet in first position with heels together and toes externally rotated. They completed one sauté jump at a time, bending the knees and jumping into the air with straight legs from a static position, landing first on the toes and transferring weight to the midfoot and heel. They repeated this process until 10 successful trials were collected; unsuccessful trials (improper landing, moving feet too soon after landing, etc.) were discarded. After the initial testing session, participants disclosed any and all dance-related injuries sustained over the course of 4 months through weekly online questionnaire check-ins, and a qualitative analysis was conducted to compare average CV between injured and non-injured dancers. The original intent was to run a regression analysis to examine the relationship between intra-limb coordination variability and injury incidence, however the number of participants (n = 8) was too low.

Data Analysis: To assess participants' coordination, angle-angle plots were created using 3-dimensional spatial information collected during dance move trials, as described by Heiderscheidt et al. (11) and modified vector coding analysis was used to quantify intra-limb coordination as described by Needham et al. (29) and Chang et al. (30). Circular statistics were executed in Excel (v16.0.13901.20400, Microsoft, Redmond, WA) and were used to calculate the between-trial mean and standard deviation of coordination data across all 10 of the sauté jump trials. Average standard deviation across the initial landing phase of the jump task was selected as the measure of variability of joint coordination (30).

Statistical Analysis: Using the values calculated for coordination and intra-limb coordination variability, a linear regression equation was intended to be fitted to the data using IBM SPSS Statistics software (v.28.0.0.0, IBM, Armonk, NY, USA) to analyze the strength of the relationship between these predictor variables and the outcome variable, injury incidence. Due to the small number of participants, a qualitative analysis was instead completed using descriptive tables of participant data and average CV graphs created on MATLAB software (R2021a, MathWorks, Natick, MA, USA) to compare shape and timing of the CV series from 0-100% of the landing phase. To determine if significant differences existed between independent variables, independent samples t-tests were run between injured and non-injured groups for the following variables using SPSS: average CV for the three couplings, hours per week spent in dance class, and experience. Significance was set to alpha = 0.05. Effect sizes (Cohen's *d*) were calculated by hand using the following equation:

$$Cohen's\ d = [\frac{M_2 - M_1}{SD_{pooled}}], \text{ where } SD_{pooled} = \sqrt{(\frac{SD_1^2 + SD_2^2}{2})}\ ,$$

Cohen's *d* results were defined as small (0.2), moderate (0.5), and large (0.8) as cited by Pollard et al. (19).

RESULTS

Descriptive information about each of the eight (8) participants that completed the study can be found in Table 1. Participants were all female dancers between the ages of 19-22, who engaged in an average of 5.81 ± 3.88 (range 3.23 – 8.79) hours of dance class or rehearsal per week, and had an average of 15.13 (range 11 – 20) years of dance experience in the following modalities: ballet (n = 8), modern/contemporary (n = 8), jazz (n = 7), tap (n = 5), hip hop (n = 5), acrobatic (n = 2), theatrical/lyrical (n = 2), clogging (n = 1), and tumbling (n = 1).

Of the eight participants, three (3) sustained at least one injury during the course of the study: participants #1, #4, and #5. Details about these injuries can be found in Table 4. Out of the three injured participants, one suffered an acute injury and two suffered chronic injuries that lasted 2 weeks each. Participant #1 suffered an acute back muscle strain during dance rehearsal when picking up a partner and did not miss any dance rehearsals or carry the injury into subsequent weeks. Participant #4 suffered a gradual, chronic injury of insidious origin to their hip and ankle for two weeks, and ended up taking 4 days off during the second week to allow the injury to heal. Participant #5 suffered a chronic foot/ankle injury for two consecutive weeks, but did not take off any time from dance because of it. As shown in Table 3, the number of hours of dance per week for injured dancers were 3.66 ± 0.75, 8.6 ± 5.07, and 5.03 ± 3.28 for participants #1, 4, and 5, respectively. Average dance hours per week for the injured group was 5.76 ± 3.03 hours, and 5.84 ± 4.38 hours for the non-injured group. Experience in years for injured dancers were 17, 13, and 13 for participants #1, 4, and 5, respectively. Average experience for the injured group was 14.33 years, and 15.60 years for the non-injured group.

As shown in Table 5, there were slight differences in average CV between injured and non-injured dancers across all 10 sauté trials. In coupling 1 – sagittal ankle and frontal ankle, or ankle dorsi/plantarflexion and ankle inversion/eversion – the average CV for the injured dancers was 20.05 and the average for the non-injured dancers was 36.33, a difference of 16.28. Results from an independent samples t-test revealed a significance of 0.051 and an effect size of 2.31 between the injured and non-injured groups.

For coupling 2, which was defined as frontal ankle and frontal knee motion, or ankle eversion/inversion and knee valgus/varus motion, average CV for the injured group was 43.69 and the average for the non-injured group was 52.62, a difference of 8.93. This difference between groups is not quite as large as the first coupling. Looking at individual average CV values for this coupling, many injured and non-injured values were fairly similar, with the exception of three outliers within the non-injured group – participant #3 (31.80), participant #7

(62.52), participant #8 (77.67). Results from an independent samples t-test revealed a significance of 0.414 and an effect size of 0.78 between the injured and non-injured groups.

For coupling 3, which was defined as sagittal ankle and sagittal knee motion, or ankle dorsiflexion/plantarflexion and knee flexion/extension, average CV for the injured group was 9.75 and the average for the non-injured group was 19.41, a difference of 9.66. This difference is similar in amount to that of coupling 2. Results from an independent samples t-test revealed a significance of 0.310 and an effect size of 1.59 between the injured and non-injured groups. Looking at individual average values for this coupling, low and high average CV values were observed in both injured and non-injured groups, and thus any kind of tendency is indiscernible.

Graphs representing 1-100% of the sauté landing phase coordination variability across all 10 trials for each participant in all 3 couplings can be found in Figures 1-3. Coupling 1, ankle sagittal plane and ankle frontal plane motion (dorsi/plantarflexion and eversion/inversion) revealed coordination variability around 20 in value for most participants (both injured and non-injured) from 0-20% of the landing phase. From 20-30%, non-injured participants #3 and #8 had spikes in their CV. Around 40% of the landing phase, non-injured participants #3, 6, 8 and 9 displayed fluctuations in their CV, most gradually trending upward toward the end of the landing phase from 90-100%. In contrast, injured participants #1, 4, and 5 displayed fairly small CV until about 60-70% of the landing phase, where all 3 display visible jumps in their CV, which lasts for #1 and 4 until 100% of the landing phase but returns to baseline for #5 from 90-100%.

Coupling 2 was defined as ankle frontal and knee frontal plane motion (eversion/inversion and valgus/varus motion), and the graph of this coupling for all participants showed varied results. Non-injured participants #3, 6, 7, 8, and 9 showed many peaks and fluctuations in average CV early on in the landing phase, while injured participants #1, 4 and 5 showed flat CV series until about 30-40% of the landing phase, at which time there were small fluctuations but still nominal values. Participants #1 and 4 show markedly increased average CV from 50-70% and 80-100%, while participant #5's largest peak in CV was around 90% of the landing phase. In the non-injured participants, there were no clear instances where average CV peaked; instead there were periodic peaks and troughs for the entire series from 0-100% of the landing phase.

Coupling 3 was defined as ankle sagittal plane and knee sagittal plane motion (dorsi/plantarflexion and flexion/extension), and this figure showed the most consistent of results between all participants out of all three couplings. Each participant's series displayed constant values from 0-30% of the landing phase, where participants #1, 5, 3, and 7 all showed a slight uptick in average CV and participants #8 and 9 showed a more substantial increase in CV. Participant #4 displayed one main peak in CV around 50-70% of the landing phase, while participants #1, 5, 6, 8 displayed main peaks in CV around 75-90%. CV valued increased substantially right before 100% of the landing phase for all injured and non-injured participants with the exception of participant #4. Furthermore, participant #7 and #9 displayed the fewest fluctuations in average CV during the entire series of 0-100% of the landing phase; these two participants' graphs were constant until 90-100%. Lastly, it is important to note that while the series were similar in shape and timing for all participants in this coupling, the injured participants' y-axes were a smaller scale than the non-injured participants', indicating what appears to be overall smaller average CV values for participants #1, 4 and 5 than the rest for the coupling.

DISCUSSION

The purpose of the current study was to determine the relationship between individual movement strategy and injury incidence in collegiate dancers by conducting linear regression analysis. Due to a very small number of participants ($n = 8$), the original plan for analysis via linear regression was no longer a possibility. The original linear regression would have used injury as the dependent variable and the following as independent variables: average CV of the dominant limb for each of the 3 couplings, average hours per week spent in rehearsal or performance, and years of experience. The goal was to determine if CV in any or all of the 3 couplings were strong predictors of injury. In theory, the study would have needed ~30 participants for each of the 5 independent variables in order to maintain appropriate statistical power. However, due to the COVID-19 pandemic and the NMU dance program being in its inaugural year, obtaining more than 100 participants was simply not practical or even possible (41).

Despite not being able to complete statistical analysis as planned, a qualitative analysis of the data was still possible, along with independent samples t-tests to validate the significance of the differences between injured and non-injured groups. The results of this analysis indicated some interesting tendencies relating injury and CV. To begin, the average CV for each coupling from Table 1 revealed that injured dancers appeared to have lower CV scores than non-injured dancers. While this may seem promising, results from the independent samples t-tests revealed no significant differences across injured and non-injured groups for any of the couplings. What is important within the results of the t-tests is that for coupling 1, the significance was $p = 0.051$, which is very close to the set alpha level of 0.05. Furthermore, this coupling revealed an effect size of 2.31, which indicates a very large effect. Medium-to-large effect sizes were seen in couplings 2 and 3 despite having very large p-values. However, there were still overlapping or similar average CV values across the two groups for all three couplings, meaning that there was no clear cutoff point or value for low CV in the injured group and high CV in the non-injured group.

An examination of the graphs of average CV across 1-100% of the landing phase for each of the participants indicated some interesting differences between non-injured and injured groups. In Figure 1 for coupling 1, injured participants tended to have flat, constant CV levels until about 70-100% of the landing phase, where the CV values spiked and increased for participants #1 and 4, but peaked and fell for participant #5. In general, non-injured participants appeared to have overall higher CV values and more frequent fluctuations than the non-injured group, with the exception of participant #7 whose graph appeared visually similar to those of the three injured participants. In Figure 2 for coupling 2, the only clear difference between the injured and non-injured group was that the non-injured group had more periodic peaks and troughs in average CV across the entire 0-100% of landing phase, while the injured participants had only one or two major peaks at the middle to end of landing. Aside from this difference, peak average CV values were roughly the same or similar across both groups. In Figure 3 for coupling 3, the shape and timing of the average CV series were similar across both injured and non-injured groups. However, one important difference between groups for this coupling can be found on the y-axes: on average, the injured groups' graphs had a much smaller y-axis scale which appears to indicate overall lower average CV for this group across the entire landing phase for coupling 3.

How do these results compare with previous literature? In general, the higher the variability of a coordinative structure, the healthier the system, and conversely, the lower the variability, the more pathology tends to emerge (9). The results from the current study show slight support of this theory, especially in coupling 1. Additionally, it is still unclear if injury results from or causes lowered CV; the only fact supported by previous literature is that injury and a lowered state of CV are related (9,20,19,24). It would be interesting to follow the participating dancers for another calendar year to see how injury trends emerge longitudinally.

The CV couplings in this study were selected based on dysfunctional movement patterns associated with common lower extremity injuries in dance. Coupling 1, ankle sagittal plane and ankle frontal plane motion, is associated with ankle inversion sprains, which often occur via an inversion and plantarflexion mechanism (31,32). Results from the independent samples t-test between injured and non-injured groups for this coupling were very close to the set significance level of 0.05 and the effect size for this difference was very large at 2.31. These results are particularly interesting because both participant #4 and 5 sustained ankle or foot injuries during the course of the study. The overall average CV for all participants in this coupling was 30.48, which both individual scores are well below (15.30 and 24.79, respectively). It is well documented that ankle sprains are some of the most common injuries in dancers of all ages and experience levels (3,12,13,26,33,34).

Coupling 2, ankle frontal plane and knee frontal plane motion, is associated with knee injuries such as ACL injuries, which often occur with ankle eversion and knee valgus motion in these planes (35). None of the injured dancers in this study sustained any kind of knee injury, which may be due to the hypothesized protective effect of rigorous and repetitive jump and balance training to protect dancers from ACL injury (36). Furthermore, one study recorded a higher risk of ACL injury in one classical ballet company than in two contemporary dance companies, indicating this injury may be modality-specific (37). The dancers in the current study came from backgrounds of mixed dance modality. Coupling 3, ankle sagittal plane and knee sagittal plane motion, is associated with overuse injury resulting from repeated force absorption during landing from a jump (9,12). Two of the three dancers in the current study sustained overuse injuries, and their average CV for coupling 3 was 9.09 (participant #4) and 10.42 (participant #5), which were both below the overall participant average for that coupling (17.04).

Previous dance injury studies have found that as dance exposure or amount of time spent dancing per week increases, so increases injury incidence (3,25,33). In the current study, one of the injured dancers (participant #4) had the second highest individual average of hours spent in dance per week (8.6 ± 5.07 hours; cohort average 5.81 ± 3.88 hours), but the other two injured dancers (participants #1 and 5) engaged in either less (participant #1: 3.66 ± 0.75 hours) or very close to (participant #4: 5.03 ± 3.28 hours) the group average (5.81 ± 3.88 hours). It is evident that the number of hours spent in dance class or rehearsal per week was not a major indicator of injury risk in the current study, however, future longitudinal research with a much larger group of dancers is warranted to more accurately determine the relationship between number of hours spent dancing per week and injury.

In line with previous literature, all three of the injured dancers suffered injuries to their lower extremity or back. Many studies have documented that back and lower extremity injury are common in dancers due to a number of reasons, including dancing on hard flooring, complicated jumps and landings, and uncomfortable footwear (2,4,5,12,26,39). Two out of the three injured dancers sustained chronic injuries that lasted two or more weeks. Previous studies provide mixed results about whether chronic or acute injuries are more common in dance; the majority have found overuse to be the most common type of injury in dancers

(2,4,12,26,33,34,40), although others have found acute injuries to be more common than overuse (3).

As mentioned previously, there were significant limitations in the current study. First and foremost, the combination of the COVID-19 pandemic and the NMU dance program being in its inaugural year significantly limited the number of participant volunteers (41). Due to the low number of participants (n = 8), low statistical power, and multicollinearity in some of the independent variables, the original plan for statistical regression analysis had to be replaced by qualitative analysis. While the qualitative analysis above is primarily subjective in nature, it does highlight certain tendencies that warrant future investigation. It would be worthwhile to replicate the current study with a much larger participant pool (n > 100) over a longer period of time (ideally > 1 year) in order to run a linear regression equation to accurately represent the relationship between the dependent variable, injury, and the following independent variables: coordination variability, hours of dance per week, and experience level. Despite these limitations, this study highlighted certain trends which point to a relationship between lower coordination variability and injury in dancers.

Tables and Figures

TABLE 1. Pre-study eligibility questionnaire.

Section 1	Q1	Name (first & last)?
	Q2	Age (in years)?
	Q3	Height (in inches)?
	Q4	Weight (in pounds)?
	Q5	Years of dance experience?
	Q6	What year did you start dancing?
	Q7	What is your main dance technique? (Jazz, Ballet, Modern/Contemporary, Tap, Other)
	Q8	Average hours per week spent in rehearsal in the last 1-3 years?
	Q9	Have you had any previous injuries? If yes, move on to Section 2.
Section 2	Q10	Which body parts have you injured in the past? Please check all that apply. (Neck, Shoulder, Arm, Elbow, Wrist, Hand, Spine, Ribs, Hip , Thigh, Knee, Ankle, Foot)
	Q11	Which of these injuries were dance-related?
	Q12	When was your most recent injury? Move on to Section 3
Section 3	Q13	When was your most recent injury? (1-3mo., 4-6mo., 7-9mo., 10-12mo., >12mo.)
	Q14	What was your most recent injury? Please describe here.
	Q15	Did you need any of the following with your last injury? (Cast/Crutches/Brace/Surgery)
	Q16	How long did you take off from dance because of your last injury? (0wk., 1-3wk., 4-6wk., 6+wk.)
	Q17	Does your most recent injury still bother you or keep you from performing certain movements in dance? (Yes/No/Maybe – please explain)
Section 4	Q18	Do you have any questions or concerns you would like the researchers to know about?

TABLE 2. Weekly dance injury check-in questionnaire.

Section 1	Q1	Name?
	Q2	Date (M/D/Y)?
	Q3	How many hours did you spend in dance class or rehearsal this week?
	Q4	How many hours on Monday?
	Q5	How many hours on Tuesday?
	Q6	How many hours on Wednesday?
	Q7	How many hours on Thursday?
	Q8	How many hours on Friday?
	Q9	How many hours on Saturday and Sunday?
	Q10	During the past week, did you experience any injuries DIRECTLY RELATED to dancing in class or rehearsal? (Yes = go to Section 2; No = Section 6)
Section 2	Q11	Which part of your body has the injury? (Shoulder, Arm, Elbow, Wrist, Hand, Hip, Thigh, Knee, Ankle, Foot, Neck/Head)
	Q12	Can you describe what happened during the injury?
	Q13	Have you sought medical attention for this injury? (Go to Section 3)
Section 3	Q14	Has your injury been diagnosed by a medical professional (MD, DO, PT, AT)?
	Q15	If YES to the question above, what was the official diagnosis?
	Q16	Was your injury sudden (acute) or more of a gradual onset (chronic)? (Acute = Section 4; Gradual/Chronic = Section 5)
Section 4 (Acute)	Q17	What type of injury? (sprain, tear, break, bruise, other)
	Q18	Please describe the injury?
	Q19	Did your doctor recommend taking time away from dance to heal? (Go to Section 6)
Section 5 (Chronic)	Q20	Has this injury carried over from last week?
	Q21	If YES to the question above, on what date did the original injury occur?
	Q22	What kind of injury is it? If you select 'Other', please describe or list the injury. (stress fracture, tendonitis, muscle strain)
	Q23	Have you taken time off from dance or other physical activities directly because of this injury?
	Q24	If YES to the above question, how many days have you had to take off from dance or other physical activities? (Go to Section 6)
Section 6	Q25	Do you have any questions or concerns you would like the researchers to know about?

TABLE 3. Descriptive data for 8 participants who successfully completed $10 \leq x \leq 21$ weeks of weekly injury check-ins.

Participant	Age (years)	Dominant Leg	Dance hours per week (Mean ± SD)	Experience (years)	Modality	Injury
1	21	Right	3.66 ± 0.75	17	1, 2, 3, 9	Y
3	20	Right	6.58 ± 4.36	17	1, 2, 3, 5, 6, 7	N
4	20	Right	8.6 ± 5.07	13	1, 2, 3	Y
5	21	Right	5.03 ± 3.28	13	1, 2, 3, 4, 5	Y
6	20	Right	5.55 ± 5.72	11	1, 2, 3, 4	N
7	20	Right	8.79 ± 6.88	17	1, 2, 3, 6	N
8	19	Right	3.23 ± 0.83	13	1, 2, 3, 4, 5, 7, 8	N
9	22	Right	5.05 ± 4.12	20	1, 2, 3, 4, 5	N
Average (group)	20	--	5.81 ± 3.88	15.13	--	--
Average (injured)	20.67	--	5.76 ± 3.03	14.33	--	--
Average (non-injured)	20.20	--	5.84 ± 4.38	15.60	--	--
Significance of diff (inj. vs. non)	--	--	p = 0.964	p = 0.609	--	--

Note. Dance modality numbers correspond to: (1) ballet, (2) modern/contemporary, (3) jazz, (4) tap, (5) hip hop, (6) acrobatic, (7) theatrical/lyrical, (8) clogging, (9) tumbling. Results of independent samples t-test between injured and non-injured groups are in gray highlighted cells. Significance set to alpha = 0.05.

TABLE 4. Descriptive data for 3 participants who sustained x ≥ 1 injury throughout the 21 weeks of study.

Participant	**Body part Injured**	**Type**	**Mechanism**	**# injured weeks**
1	Back	Muscle strain	Acute	1
4	Hip, ankle	Sprain	Chronic	2
5	Ankle, foot	Sprain	Chronic	2

TABLE 5. Average coordination variability (CV) across all 10 trials for each coupling.

Dominant Leg Coupling; Average CV across all trials			
Participant	**Ankle X + Ankle Y**	**Ankle Y + Knee Y**	**Ankle X + Knee X**
1	***22.14***	***42.23***	***19.78***
3	50.44	31.80	25.15
4	***15.30***	***39.96***	***9.09***
5	***24.79***	***47.42***	***10.42***
6	38.10	43.54	21.55
7	23.74	62.52	11.99
8	39.73	77.67	28.26
9	29.64	47.55	10.12
Average (with injured)	30.48	49.09	17.04
Average (non-injured.)	36.33	52.62	19.41
Average (injured)	20.05	43.69	9.75
Significance of diff. (inj. vs. non)	0.052	0.414	0.310
Effect size (Cohen's *d*)	2.31	0.78	1.59

Note. Injured participants are denoted with bolded, italicized text. Results of independent samples t-test and effect size between injured and non-injured groups are in gray highlighted cells. Significance set to alpha = 0.05.

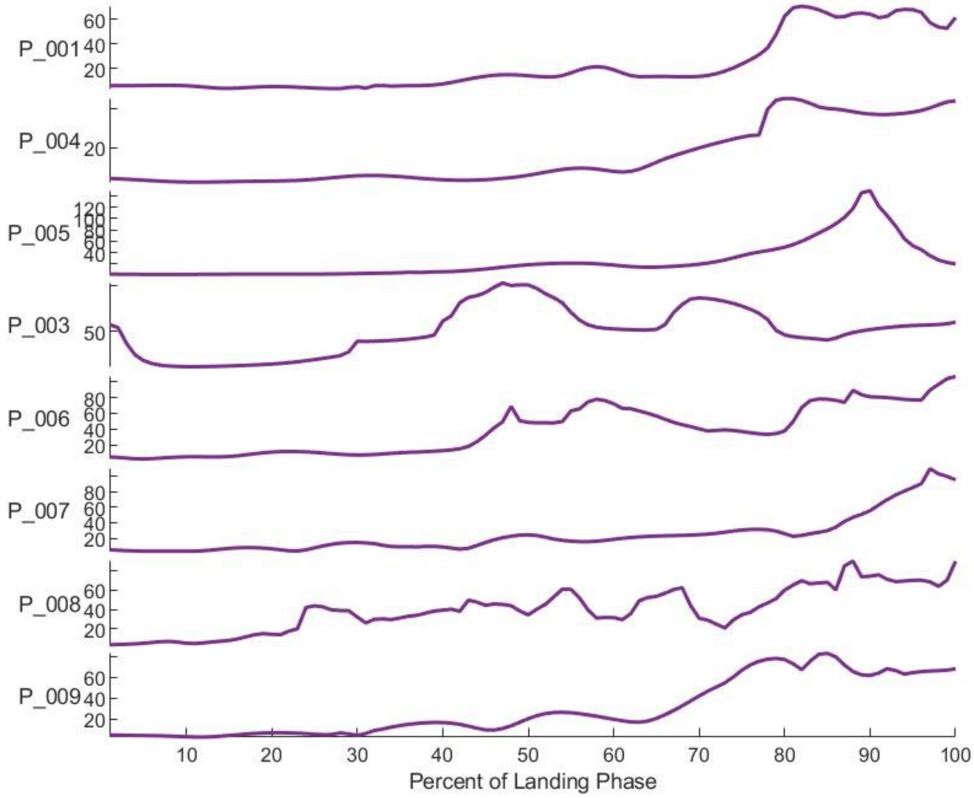

Figure 1. Average coordination variability across all 10 trials from 1-100% of the sauté landing phase for coupling 1: ankle sagittal plane and ankle frontal plane (dorsi/plantarflexion and eversion/inversion). Y-axis labels correspond to participant numbers. Injured participants (#1, 4, 5) are the first 3 series at the top of the figure.

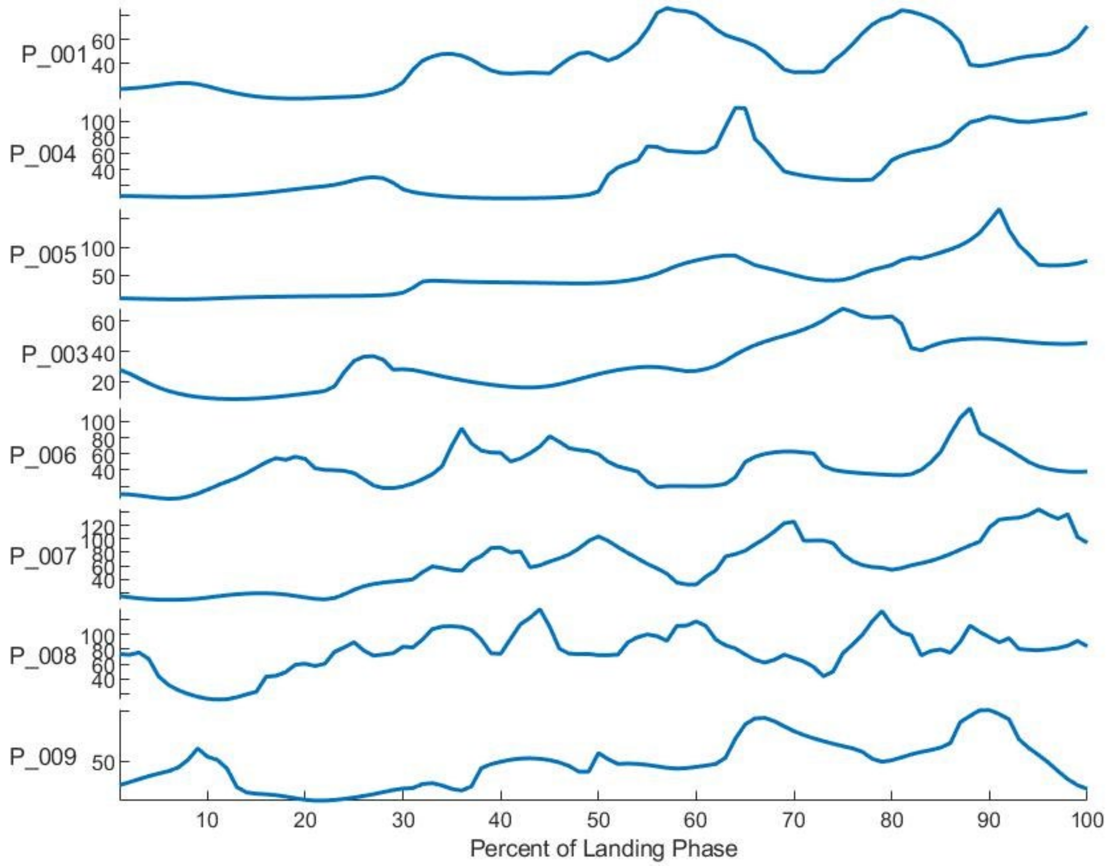

Figure 2. Average coordination variability across all 10 trials from 1-100% of the sauté landing phase for coupling 2: ankle frontal plane and knee frontal plane (eversion/inversion and knee valgus/varus motion). Y-axis labels correspond to participant numbers. Injured participants (#1, 4, 5) are the first 3 series at the top of the figure.

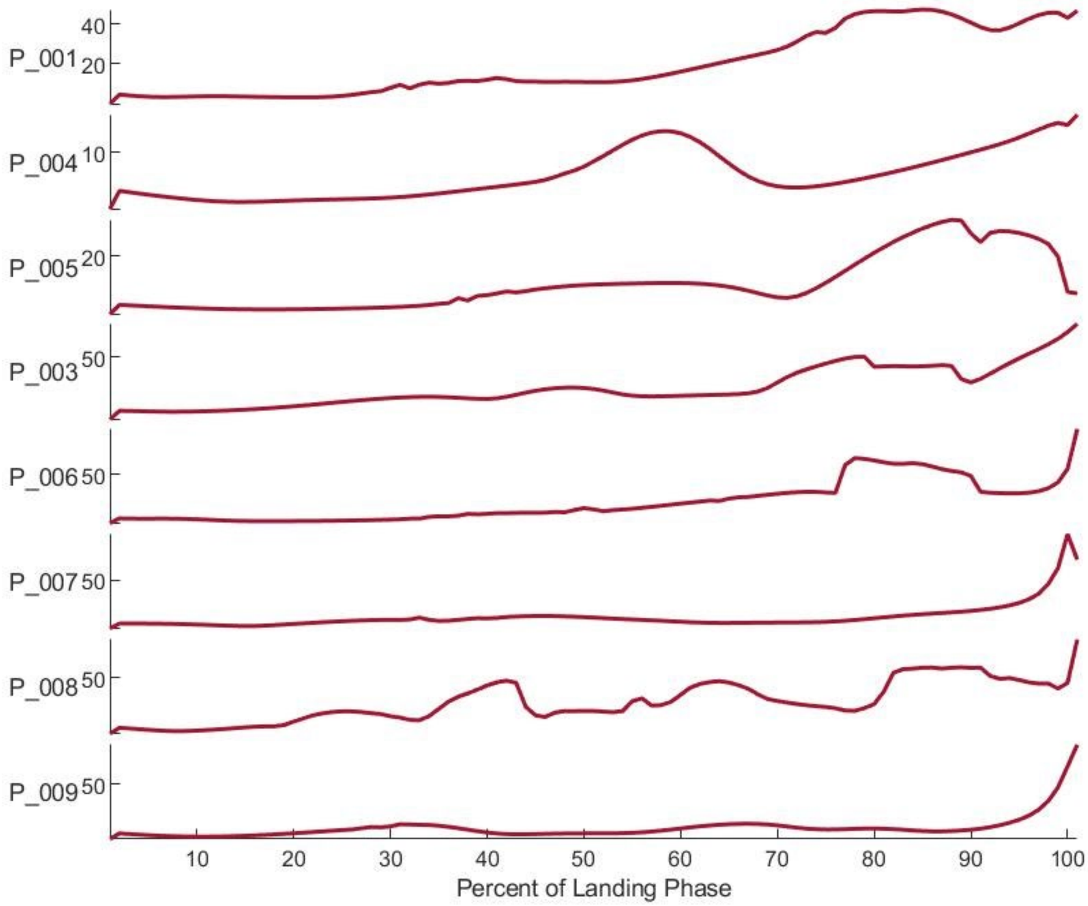

Figure 3. Average coordination variability across all 10 trials from 1-100% of the sauté landing phase for coupling 3: ankle sagittal plane and knee sagittal plane (dorsi/plantarflexion and flexion/extension). Y-axis labels correspond to participant numbers. Injured participants (#1, 4, 5) are the first 3 series at the top of the figure.

CHAPTER II: LITERATURE REVIEW

1. **Overview**

This chapter will introduce dance and discuss biomechanical concepts central to assessing dance as an athletic endeavor and a sport. Literature about this subject area was assembled from a variety of academic disciplines including exercise science, motor control and behavior, biomechanics, and sports medicine. A thorough search of Northern Michigan University's online library catalog, PubMed journal database, and Google scholar were conducted to find articles within the aforementioned subject areas. Keywords used to search included dance, dance injury, ballet, contemporary, jazz, ankle sprain, ACL injury, lower extremity, coordination, coordination variability, vector coding, dynamical systems theory, and motor control. Exclusion terms included children, beginner, partner dance.

2. **Dance**

2.1. Dance as a Sport

Dance is a sport that requires a great deal of athleticism to perform. Dancers are a unique category of athlete in that they are required to possess physical capabilities such as muscular strength and endurance, aerobic and anaerobic energy utilization, speed, agility, coordination and motor control (18), all the while maintaining precise visual consistency in their movements (2,6,15,42). In this way, dancers are simultaneously athletes and artists (4).

There are a variety of dance modalities, all with their own set of physical demands. Perhaps the most widely recognized modality of dance is ballet; this style emphasizes long, straight lines, elegant movements, and lightness on one's feet. Modern or contemporary is another popular style of dance. This style emphasizes raw athleticism, creation of unique shapes with one's own body or a partner, and expressive movements to evoke an emotional response from the audience. Other modalities of dance include tap, jazz, hip-hop, folk and Irish.

Each of the aforementioned dance styles shares the following physical demands: long hours spent in practice/rehearsal (3), dancing barefoot or in ill-fitting, specialized shoes (25,33), repetitive explosive vertical and horizontal jumping and landing movements (5,12,16,26), extreme ranges of motion (27,43,44), and balance (13). For the purpose of this literature review, all dance styles will be considered collectively instead of individually.

2.2. Dance as a Movement Task

In this section, common dance movements and specific physical attributes required of dancers will be discussed. Common movements performed by dancers across all modalities include bipedal and unipedal jumps (jumping or landing on two legs and one leg, respectively) (1,5,12,16,18), turns, choreographed falls (6), and squat variations (1). Dancers must possess several athletic characteristics in order to meet the physical demands of the above listed movements and thus be successful in their sport. Among these important characteristics for dance are overall flexibility (specifically hip, foot, and ankle), strength (most notably spine and core), body proportions, stability and control, and coordination (45).

2.3. Dance Anatomy

In order to understand dance as a sport and a movement modality, it is important to consider the underlying anatomical and physiological features of the human body and how these various structures work together to produce dynamic movements. There are two main areas for consideration: the skeletal system and the neuromuscular system.

First, the skeletal system supplies the human body with a rigid base of support during weight-bearing activities. The adult skeletal system is made up of 206 bones, which serve the following 5 key functions in the body: support for stability and form, protection of vital internal organs, movement by way of levers created from muscle attaching to bone, red blood cell production in bone marrow, and mineral storage (46). For this analysis, the most important functions of the skeletal system are support and movement.

The skeleton can be divided into axial and appendicular regions. The axial skeleton is made up of the skull, vertebral column, sternum, and ribs, while the appendicular skeleton consists of the upper and lower extremities (47). Dancers draw heavily upon both of these regions when creating and executing expressive dance choreography movements. For example, in a simple sauté, the dancer starts in first position with their heels touching and toes pointing outward at approximately a 45-degree angle. This movement alone involves over 60 bones supporting the lower body during a jump. They bend their knees into a plié, then immediately push off their heels and toes to jump into the air with straight legs and pointed toes, landing toes first, then heels, back in first position. In this example, the lower body - supported by the appendicular skeleton - produces movement to propel the dancer in the air. However, the lower body is not the only part of the skeleton that assists the movement. The pelvic girdle, spine, head, and arms also contribute to the movement through force transferring up the kinetic chain throughout the jump and landing. Without the bones of the upper body (both axial and appendicular), the upper body would simply be a limp passenger in the movement.

The second component for this anatomical analysis of dance is the neuromuscular system. Without muscles and nerves to provide power and movement, the skeleton would be a passive structure on its own. The lower body is composed of the pelvic girdle, the femur, tibia, fibula, patella, tarsal bones, metatarsals, and phalanges. On top of these bones lie the muscles of the lower body; major muscle groups include the gluteal group (hip extension and stability) quadriceps (knee extensors), hamstrings (knee flexors), soleus and gastrocnemius (plantarflexion of the foot), flexors and extensors of the foot, and intrinsic foot muscles. Contractions of these muscles via neural impulses from the central and peripheral nervous system create movement. Force from contracted muscles is transferred to the skeleton via tendons, which causes motion in the involved skeletal structures.

In the above example of the sauté jump, the brain conveys information via neural impulses from the central nervous system to the peripheral nervous system to activate motor units controlling the eccentric contraction of the knee extensors to bend the knee into a plié – the jump preparation phase. Pushing off the heels and toes while jumping involves plantarflexion, knee extension, and hip extension; landing requires plantarflexion to dorsiflexion as the feet absorb force, and knee and hip flexion as the absorbed force moves up the kinetic chain. Without signals from the nervous system to execute these actions, it would not be possible to complete the movement at all.

3. **Dance Injury**

3.1. Overview

Considering the physical demands of the sport and the heavy involvement of the lower extremity, injury is common in dance. Dancers spend many hours in practice, rehearsal, and performance, and are thus exposed to injury with each added exposure (25). Injuries can be classified as traumatic (sudden onset) or overuse (gradual onset). Common injuries in this population include ankle sprains, knee injuries (such as ACL tears), metatarsal fractures, and back muscle strains. Much of the existing literature on dance injury agrees that overuse injuries tend to be the most common across all levels and types of dancers (2,4,12,26,33,34,40). However, one study specific to ballet dancers found that amateur dancers showed a higher proportion of overuse injuries than professionals, and male professional dancers showed a higher proportion of traumatic injuries than female and amateur dancers (2). Traumatic injuries are less common, but still significant (4,25,33).

By far the most common injured body region in dance is the lower extremity, which includes the hip, thigh, knee, lower leg or shank, ankle, and foot (4,33,34,38,39,48). Injury to the lower extremity often occurs in non-contact situations like landing from a jump, whether it be a one- or two-legged landing (16,31,36) and this is largely due to improper lower extremity alignment and neuromuscular control (16). Ankle sprains (13,33,34), metatarsal fractures (33,34), ACL tears (36,37), thigh muscle strains or tears (4), and tibial stress fractures (4) are among the most frequent overuse and traumatic ailments experienced by dancers.

3.2. Ankle Sprain

The ankle joint is also known as the talocrural joint, which is where the tibia and fibula articulate with the talus of the foot. These three bones are held together by many ligaments that provide passive stability to the joint as it moves through its range of motion. Ligaments on the lateral side of the ankle include the posterior talofibular, the calcaneofibular, and the anterior talofibular ligament. On the medial side of the ankle lies the deltoid ligament which is made up of 4 smaller ligaments that act together to provide stability. Injury to these structures is common especially in sports that involve uneven surfaces or jumping and landing.

Ankle sprains are one of the most common injuries that result in individuals seeking medical care (49). It is estimated that about 40% of all lateral ankle sprains occur during sports (49) The mechanism of injury for an acute lateral ankle sprain involves sudden inversion of the ankle coupled with plantarflexion of the foot (31,32). This can happen while landing from a jump, cutting during running, or running on uneven surfaces (49). Other less common ankle sprains are medial or eversion sprains which involve a sudden inversion or pronation moment of the ankle, and high ankle sprains which involve injuries to the ligaments that connect the tibia and fibula in the shank (50).

Dancers are especially susceptible to ankle sprains; ankle injuries are some of the most commonly reported injuries in dancers across all skill levels (12,13,26,33). Of all dance-related ankle injuries, inversion sprains are the most common traumatic injury in dancers, which is largely due to the extreme positions created when dancing on pointe on demi-pointe, or even on the balls of the feet with the foot in a plantar flexed position (33). These positions can lead to both acute (traumatic) sprains of the foot and ankle, as well as overuse injuries to the same structures. Other contributing factors include anatomical alignment, poor training, technical errors, unfamiliar choreography or style, and environmental factors including flooring surface (33).

3.3. ACL Injury

The anterior cruciate ligament is a soft tissue located between the femur and tibia in the knee joint and is imperative for knee stability during many activities of daily living. Injuries to the anterior cruciate ligament (ACL) are a common occurrence in athletic populations. ACL injuries are prevalent in sports that require pivoting and jumping (35). The typical mechanism of injury is non-contact (35); often this involves internal rotation, or valgus collapse, of the knee (51).

The relationship between dance and ACL injury risk is unclear. Literature cites that the lower extremities are most susceptible to injury in dancers (4,33,34,38,39,48), and ACL injury is a commonly recorded injury in dancers (36,37). However, despite the fact that dancers frequently perform single- and double-legged jump landings, they have displayed lower ACL injury rates than in other sports (16). One potentially significant difference between dancers and other athletes is that dancers perform jumps and landings over and over again, while non-dancing athletes perform jumps and landings only as needed. Additionally, dance training emphasizes a soft landing with the ankle in dorsiflexion and the knee bent (16), while athletes in other sports may be landing and changing direction abruptly.

4. **Coordination**

4.1. Overview

From a dynamical systems perspective, movement of the human body is a complex process involving many different biological systems, for example, muscular, skeletal, respiratory, integumentary, circulatory, etc. (51). Each available component of the biological system is referred to as a degree of freedom (DOF). In order to produce a desired movement, one must organize the available degrees of freedom (i.e. joints, segments, muscles) into a coordinated effort (7). As one might expect, there are many different ways to organize movements within the available degrees of freedom, and thus, each possible human movement exhibits substantial variability.

4.2. Dynamical Systems Theory

At the foundation of healthy movement patterns lies the effective organization of multiple degrees of freedom within the neuromuscular system (7,52). Conversely, the inability to choreograph and integrate these neuromuscular degrees of freedom is indicative of pathological or ineffective patterns of movement (53). Dynamical systems theory enables the researcher to simplify movement analysis of the neuromuscular system from many degrees of freedom to a single variable.

Dynamical systems theory specifies that movement patterns originate from organization of the neuromuscular system within [the scope of] morphological, biomechanical, and environmental factors, as well as task constraints (53). Morphological factors include the interactions between the shape, size, and orientation of structures such as bones; biomechanical factors involve the geometric properties of the musculoskeletal system and the forces or position of the limbs in space; environmental factors include the physical settings such as flooring type or weather conditions; while task constraints include the objectives or specific rules involved in performing a motor skill. Thus, it is evident that the creation and classification of movement patterns is multifactorial. Movement arises from the organization of the multiple available degrees of freedom within the human body: skeletal muscle, bone, and motor units synchronizing with one another to achieve an end goal that fits the system and environmental constraints (53).

4.3. Coordinative Structures

In the study of human biomechanics, movement systems compensate for the many - and often redundant - degrees of freedom by creating couplings between multiple degrees of freedom, called ‘coordinative structures’ (52). Coordinative structures constrain the individual components of the system during a movement, thus constraining the overall complexity of the movement system (54). Coordinative structures also enable the organism to achieve the same [movement] outcome by using different strategies or degrees of freedom (51,55).

No two of the same movements are exactly alike - for example, two strides in one participant’s gait or even two different participants’ grand jeté - thanks to slight or even overt variations in the manner in which degrees of freedom are coupled in a coordinative structure (53). That is, the movement strategy might differ from one iteration to the next simply due to the change in coupling of degrees of freedom and thus the coordinative structure. A dynamical system is one in which behaviors evolve over time (56). A central tenet to dynamical systems theory is that these variations in observed movement patterns are largely due to global and local perturbations (53).

5. **Coordination Variability**

5.1. Overview

Variability is inherent in all biological systems, and human bodies are no exception to this rule. Variability is the result of both the structural and functional characteristics of the system (in human bodies, the neuromuscular and musculoskeletal systems) and the internal and external limitations placed upon the motion of the system (57). Movement is inherently variable; considering the continuously evolving physical and environmental constraints of a performance, it is impossible to replicate a movement exactly between individuals or between trials in the same individual (57). In short, variability is how much a measure changes between individuals or between iterations of the measure executed by the same individual. Variability gives us information about the flexibility and adaptability of a system. For the purposes of this analysis, variability will refer to changes in a movement performed by one individual across several different trials.

Coordination variability is the amount of change observed in coordinative structures across trials of the same task or between individuals. Mathematically, it is defined as the standard deviation of displacement across multiple trials (15), where displacement of the body is usually measured kinematically with 3-D motion capture systems.

5.2. Coordination Variability & Performance

When it comes to performance variability, or 'endpoint' variability, expert athletes' movements should be more stable and therefore less variable than those with less experience (1,9). In terms of sport performance, the overarching goal is to decrease the degrees of freedom in a system and thus decrease the amount of variability in order to constrain the performance to a strict range of movements., One study by Arutyunyan et al. (10) showed less 'end point' variability in experienced pistol shooters. Another concept called movement variability refers to the "flexibility or stability of how a task is achieved" (1). Coordination variability is a type of movement variability and studies have shown it is often higher in experienced athletes (8-11). To illustrate this point, Arutyunyan et al. (10) documented greater coordination variability in expert shooters' individual movement strategy than novices. It is logical that athletes would display less flexibility in their performance movement patterns and more flexibility in their coordination strategies.

Dancers, who are athletes in their own right, exhibit a different relationship between coordination variability and skill. Recent studies have found that coordination variability actually decreases as skill level increases (1,12-14). Current literature has yet to explain this difference in coordination variability and skill between dancers and other athletes, however, a possible explanation could be that the aesthetic nature of dance limits coordination strategy to a range of visually appealing, choreographed movements. Support for this hypothesis comes from a study by Shih et al. (1), which measured decreased inter-limb force coordination variability in skilled dancers versus non-dancers during the transition phase in jumps. These results indicated better performance in the dancers by their ability to maintain consistent jump rate and jump height. Conversely, Jarvis et al. (15) recorded an *increase* in trunk coordination variability in experienced dancers in comparison with non-dancers during the late flight phase of a sauté jump; these results are more similar to trends seen in other sports.

To expand upon these contradicting findings, Wilson et al. (8), proposed a U-shaped trend in coordination variability levels in track and field triple jumpers. This documented trend showed high levels of coordination variability in expert jumpers, low levels of coordination variability in intermediate jumpers, and again high levels of coordination variability in novice jumpers. This U-shaped trend has not yet been observed or documented in dancers, possibly due to different skill development between the two sports. Triple jump is a sport that emphasizes distance jumped as end-goal performance, which presumably allows the athlete to choose from a variety of movement strategies during skill development to achieve this outcome, while dance emphasizes the appearance of each move, which potentially restricts skill development to a limited number of visually consistent movements. As supported by the evidence listed above, most sports performance benefits from higher levels of coordination variability. Dance may be an exception to this rule, possibly due to the constraints imposed to maintain visual appeal. The discrepancy between dance and other sports' optimal levels of coordination variability highlights a need to understand more about coordination variability, performance, and injury risk in dance.

5.3. Coordination Variability & Injury

Previous literature states that the main sources of lower extremity injuries in dancers are overuse and overtraining (2,3,12,17,18), while incorrect takeoff and landing strategy during jumps (12,16) and unexpected falls (6) are also linked to dance injury. Moreover, several studies have connected risk of acute and overuse injury to coordination variability. Pollard et al. (19) noted a relationship between lower levels of coordination variability and acute injury risk, and Lipsitz (20) introduced the "loss of complexity" hypothesis which states that injury or dysfunction tends to emerge as coordination variability decreases to a critical point.

According to Hamill et al. (9), the healthier state of a human system is one with higher coordination variability, while lower coordination variability is linked to dysfunction and injury. There is most likely an upper limit of ideal coordinative variability through which an athlete can optimally function without injury (9). A puzzling finding in a recent study on overuse injury in runners found a conflicting trend: injured runners exhibited greater knee-ankle and shank-ankle coordinative variability than non-injured runners (21). These findings bring up questions about how coordination variability contributes to overuse injury in any athletic population. The findings in the running study highlight the complex and confusing relationship between coordination variability and injury, as it is often dependent upon task phase and the task as a whole (21). In tandem with understanding how coordination variability and overuse influence athletes' injury risk, other studies have examined specific dance movements to understand how individual movement strategy differs between non-dancers and dancers and how these coordination patterns might influence injury susceptibility over time.

Among the most common movements in dance are bipedal and unipedal jumps (1,5,12,16,18), turns, choreographed falls (6), and squat variations (1). Dancers must coordinate their two lower limbs for proper style and to minimize injury during each of these movements (1,14). Vector coding is a way to measure coordination variability, through recording the three-dimensional position of a joint, segment, or limb in space during a task or phase of a task, creating angle-angle diagrams of one segment or joint in relation to one another, and assessing the motion of both points in relation to one another (9,11,12,19,21-24). Previous literature has employed vector coding to assess a range of movements including jump tasks (15). Jump tasks are commonly utilized movements in dance studies. These methods can be used in tandem with information on coordination variability and injury risk in other sports and apply both toward the assessment of the relationship between coordination variability and injury risk in dancers.

Many studies have shown that injury tends to emerge in most athletic populations as coordination variability decreases (9,19,20). Applying this theory to dance is a little less straightforward, as other studies have indicated that increasing dance skill is accompanied by decreased coordination variability (1,12-14), potentially making skilled dancers more susceptible to injury. In the general athletic population, risk of injury tends to increase with overtraining (2,3,12,17,18), landing from a jump (12,16), and in cases of lower coordination variability (9,19,20). In line with findings related to the general athletic population, we would expect to see a similar phenomenon in dancers: higher coordination variability corresponding to a healthy state and lower coordination variability indicating injury or risk of injury.

6. **Conclusion**

At present, a number of studies have described injures in dancers, (1-3,5,6,12,17,18), a few have documented injury incidence in professional dance companies over the long term (3,4,25), several have studied limb coordination and coordination variability in jumps and balance tasks (1,14), and a few have prospectively studied overuse injury risk in a range of sports settings (3,21,25,26). What is missing from the current body of literature is evidence to support or refute coordination variability as a risk factor for injury in dancers. Data supporting or refuting this relationship would highlight the importance of training variable coordination patterns in dance choreography as well as contributing to the development of screening tools to aid in the prevention of injury in certain susceptible individuals.

CHAPTER III: CONCLUSIONS AND RECOMMENDATIONS

The primary purpose of this research was to assess the relationship between coordination variability and injury in a group of experienced, collegiate dancers. Coordination variability was calculated through three-dimensional kinematic motion analysis of the lower limb, and injury incidence was collected through four months of self-reported injury questionnaires. The intended method of assessing the relationship between injury and CV was to run linear regression analysis between the dependent variable, injury, and the following independent variables: 3 CV couplings, average dance hours per week, and years of experience. However, due to a small participant pool, this analysis was not possible. Instead, a qualitative analysis of the data was conducted and showed promising preliminary tendencies within the data.

All three of the lower extremity couplings showed average CV for the injured group (n = 3) appeared to be lower than the average CV for the non-injured group (n = 5). Results from independent samples t-tests for each of these three couplings revealed an absence of significant differences between injured and non-injured groups, with the exception of coupling 1, which was extremely close to the set significance level and thus had a meaningful significant difference with a very large effect size. Results for coupling 1 were particularly interesting due to its correspondence with ankle and foot injuries, which were present in 2 out of the 3 injured dancers in this study. Graphs of the CV across 0-100% of the landing phase for each participant supported the above findings that CV appeared to be lower and had fewer peaks in injured dancers, but the extent of these differences could not be validated. These results support findings from previous literature which state lower CV and injury are related (9,19,20), however other studies have shown this relationship is dependent upon the phase of the task in question (21). Furthermore, because all dancers in the current study had at least 10 years of experience, it was not possible to discern whether or not skill or experience had an effect on the observed trends.

Due to the aforementioned limitations, it is recommended this study be regarded as pilot testing from which to model future research. Subsequent studies should focus on two main endeavors: (A) pairing with one or more dance companies from which to recruit a much higher number of participants to ensure statistical power ($n > 100$), and (B) following these dancers for a year or longer (ideally 2-3 years) in order to properly categorize injuries into acute and overuse injury as well as accurately associating number of hours of dance to injury incidence. If these two points can be achieved, it will be possible to perform statistical regression analysis for more accurate results and conclusions.

Overall, while this study did not have any statistically significant findings to definitively state whether or not CV in any of the three selected couplings were related to observed injury, a preliminary, subjective analysis showed results promising enough to warrant continued research in this area. Nevertheless, it did suggest that there are qualitative differences between injured and non-injured dancers, thus indicating the need for further research in this area.

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APPENDICIES

Appendix A
Notice of Northern Michigan University's Administrative Institutional Review Board Approval**.**

NORTHERN MICHIGAN UNIVERSITY

Graduate Studies and Research
Marquette, MI 49855-5301
906-227-2300
www.nmu.edu/graduatestudies/

Memorandum

TO: Sarah Breen
School of Health and Human Performance

Emily Klinkman
School of Health and Human Performance

DATE: February 22, 2021

FROM: Lisa Schade Eckert
Dean of Graduate Studies and Research

SUBJECT: **IRB Proposal** HS21-1168
IRB Approval Date: 2/22/2021
Proposed Project Dates: **1/18/2021 – 10/01/2021**
"Coordination variability and injury risk in experienced collegiate dancers: A prospective cohort study"

Your proposal "Coordination variability and injury risk in experienced collegiate dancers: A prospective cohort study" has been approved by the NMU Institutional Review Board. Include your proposal number (HS21-1168) on all research materials and on any correspondence regarding this project.

A. If a subject suffers an injury during research, or if there is an incident of non-compliance with IRB policies and procedures, you must take immediate action to assist the subject and notify the IRB chair (dereande@nmu.edu) and NMU's IRB administrator (leckert@nmu.edu) within 48 hours. Additionally, you must complete an Unanticipated Problem or Adverse Event Form for Research Involving Human Subjects.

B. Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding. Informed consent must continue throughout the project via a dialogue between the researcher and research participant.

C. If you find that modifications of investigators, methods, or procedures are necessary, you must submit a Project Modification Form for Research Involving Human Subjects before collecting data. Any changes or revisions to your approved research plan must be approved by the IRB prior to implementation.

Until further guidance, per CDC guidelines, the PI is responsible for obtaining signatures on the COVID-19 Researcher Agreement and Release and COVID-19 Research Participant Agreement and Release forms for any in person research.

All forms can be found at the NMU Grants and Research website:
http://www.nmu.edu/grantsandresearch/node/102

Appendix B
Notice of Northern Michigan University's Administrative Institutional Review Board Approval for project modification.

NORTHERN MICHIGAN UNIVERSITY

Graduate Studies and Research
Marquette, MI 49855-5301
906-227-2300
www.nmu.edu/graduatestudies/

MEMORANDUM

TO:	Sarah Breen School of Health and Human Performance Emily Klinkman School of Health and Human Performance
DATE:	October 21, 2021
FROM:	Lisa Schade Eckert, Dean of Graduate Studies and Research
RE:	Modification to HS21-1168 Original IRB Approval Date: 2/22/2021 Modification Approval Date: 3/30/2021 "Coordination variability and injury risk in experienced collegiate dancers: A prospective cohort study"

Your modification for the project "Coordination variability and injury risk in experienced collegiate dancers: A prospective cohort study" has been approved by the Northern Michigan University Institutional Review Board. Please include your proposal number (HS21-1168) on all research materials and on any correspondence regarding this project.

Any additional personnel changes or revisions to your approved research plan must be approved by the IRB prior to implementation. Unless specified otherwise, all previous requirements included in your original approval notice remain in effect.

Until further guidance, per CDC guidelines, the PI is responsible for obtaining signatures on the COVID-19 Researcher Agreement and Release and COVID-19 Research Participant Agreement and Release forms.
If you have any questions, please contact the IRB at hsrr@nmu.edu.