UNIVERSIDADE DE LISBOA

FACULDADE DE MOTRICIDADE HUMANA

COORDINATION PATTERNS AND BRAIN ACTIVATION DURING THE *DEMI-PLIÉ* MOVEMENT IN ITS DIFFERENT ROLES IN CLASSICAL BALLET

VIRGÍNIA HELENA QUADRADO

Orientador: Prof. Doutor Pedro José Madaleno Passos

Co-orientador: Prof. Doutor Hugo Alexandre Ferreira

Tese especialmente elaborada para obtenção do grau de Doutor em Motricidade Humana na especialidade de Comportamento Motor

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Dedico esta dissertação ao meu pai

Leonel Quadrado (in memorian)

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Abbreviations

ASIS – anterior superior iliac spine

BF – biceps femoris

CNS – central nervous system

DOF – degrees of freedom

EEG – electroencephalography

EMG – electromyography

fMRI – functional magnetic resonance image

GRF – ground reaction force

GM – gastrocnemius medialis

M1 – primary motor area

PMC – premotor cortex

PSIS – posterior superior iliac spine

RF – rectus femoris

SMA – supplementary motor area

TA – tibialis anterior

ABSTRACT

Introduction: A basic coordinated movement in classical ballet is the *demi-plié*, involving a smooth, continuous bend of the knees, keeping the thighs in external rotation (turn out) and heels on the ground. It consists of descending and ascending phases, the latter often preparing for the next move. Task goals may influence its coordination patterns, which raises questions regarding hypothetical changes in coordination modes varying with the *demi-plié* end-goal, with possible implications on interlimb coordination, muscular activation patterns, and brain cortical activation. Therefore, the aim of the present dissertation is to demonstrate whether or not different task goals require specific modes of coordination during the *demi-plié* performance linked to other ballet movements.

Methods: Thirteen classical dancers (10 female, 3 male) voluntarily participated in the experiments. Sensing technology such as motion capture, surface electromyography (EMG), and electroencephalography (EEG) were used to collect data. The experimental design involved the simple *demi-plié* performance and in preparation for four other ballet movements such as: *demi-plié* prior to relevé (i.e., heel rises); *demi-plié* prior to *sauté* (i.e., vertical jumps); *demi-plié* prior to *sissone fermée de côté* (i.e., jumps with lateral body displacement), and; *demi-plié* prior to *pirouette en dehors* (i.e., outward turns). Data analysis involved isolating the *demi-plié* from the subsequent movements, followed by analysis involving the dissimilarities of the hip vertical trajectory, knees joint angles and angular velocities, muscular activation patterns, and brain activation of the sensorimotor cortex.

Results: The results obtained from all analysis showed distinctions in the coordination patterns, muscular activation pattern, and brain cortical activation when the *demi-plié* has different end-goals. Dissimilarities of the maximum hip trajectory differences were observed in 40% for *demi-plié* prior to *sauté*, 30% prior to *sissonne fermée de cõté*, 20% prior to *relevé*, and 10% prior to *pirouette en dehors*. Dissimilarities began in the descending phase of the *demi-plié*.

ANOVAs for repeated measures and Bonferroni's *post-hoc* showed that the standard deviation of dissimilarity had the largest effect size for the comparison *demi-plié - demi-plié* prior to *sauté*, and the smallest for the comparison *demi-plié - demi-plié* prior to *pirouette*. Differences in coordination patterns in regards to the knees joint angles and angular velocities were found during the *demi-plié* performance in all five experimental conditions, showing coherence amongst all participants. Descriptive analysis focused on each muscle individually, and comparisons were made amongst the muscles for each experimental condition. Results showed significantly different patterns of muscular activation depending on the *demi-plié* end-goal. Effect size was high for each muscle, but small when compared together for each experimental condition. Significant differences were prevalent amongst the *demi-plié* in preparation for complex movements such as jumps and turns. Wavelet spectrograms showed distinct patterns of brain activation for all experimental conditions, and statistical analysis showed differences in synchronizations amongst the frequency bands alpha, low-beta, and high-beta.

Discussion: Ballet dancers may learn multiple patterns of execution of the *demi-plié* when it comes to performing subsequent complex ballet movements. *Demi-plié* prior to jumps demands plyometric forces and have open-loop motor planning, requiring acceleration, whereas *demi-plié* is a closed-loop, relying on proprioceptive updating. Differences in muscular activation during the *demi-plié* prior to other ballet movements seem to occur due to strategic anticipation foreseeing the next movement. The sensorimotor cortex seems to display different orders of activation depending on the *demi-plié* end-goal. Despite the differences in coordination patterns, some *demi-pliés* are more similar than others. We assume that the level of complexity of the ballet movement plays a role in making anticipatory adjustments in the coordination of the *demi-plié*.

Keywords: coordination pattern; brain activation; muscular activation pattern; classical ballet; *demi-plié*

RESUMO

Introdução: Um movimento básico coordenado no ballet é o *demi-plié*, que envolve uma flexão suave e contínua dos joelhos, mantendo as coxas em rotação externa e os calcanhares no chão. O *demi-plié* consiste em fases descendentes e ascendentes, esta última muitas vezes preparando para o próximo movimento. Os objetivos da tarefa podem influenciar seus padrões de coordenação, o que levanta questões sobre mudanças hipotéticas nos modos de coordenação que variam de acordo com o objetivo final do *demi-plié*, com possíveis implicações na coordenação entre membros, padrões de ativação muscular e ativação cortical cerebral. Portanto, o objetivo da presente dissertação é demonstrar se diferentes objetivos de tarefas requerem ou não modos específicos de coordenação, durante a execução do *demi-plié* vinculado a outros movimentos do ballet.

Métodos: Treze bailarinos clássicos (10 mulheres e 3 homens) participaram voluntariamente dos experimentos. Tecnologia como captura de movimento, eletromiografia de superfície (EMG) e eletroencefalografia (EEG) foram usadas para recolher dados. O desenho experimental envolveu a execução do *demi-plié* simples e na preparação para outros quatro movimentos de ballet, tais como: *demi-plié* antes do *relevé* (ou seja, elevação dos calcanhares); *demi-plié* antes do *sauté* (ou seja, saltos verticais); *demi-plié* antes do *sissone fermée de côté* (ou seja, saltos com deslocamento lateral do corpo), e; *demi-plié* antes da *pirouette en dehors* (ou seja, voltas sob uma perna de apoio). A análise dos dados envolveu o isolamento do *demi-plié* dos movimentos subsequentes, seguido pelas análises envolvendo as diferenças da trajetória vertical do quadril, ângulos articulares dos joelhos e suas velocidades angulares, padrões de ativação muscular e ativação cortical cerebral.

Resultados: Os resultados obtidos em todas as análises mostraram distinções nos padrões de coordenação, no padrão de ativação muscular e na ativação cortical cerebral quando o *demi-plié* tem objetivos diferentes. Dissimilaridades da trajetória máxima do quadril: diferenças

de 40% para o *demi-plié* antes do *sauté*, 30% antes do *sissonne*, 20% antes do *relevé* e 10% antes da *pirouette.* As diferenças começaram na fase descendente do *demi-plié*. As ANOVAs para medidas repetidas e o post-hoc de Bonferroni mostraram que o desvio padrão de dissimilaridade teve o maior tamanho de efeito para o par *demi-plié - demi-plié* antes do *sauté*, e o menor para o par *demi-plié - demi-plié* antes da *pirouette*. Diferenças nos padrões de coordenação em relação aos ângulos articulares dos joelhos e velocidades angulares foram encontradas durante a execução do *demi-plié* em todas as condições experimentais, mostrando estabilidade entre todos os participantes. A análise descritiva focou em cada músculo individualmente, e foram feitas comparações entre os músculos para cada condição experimental. Os resultados mostraram padrões significativamente diferentes de ativação muscular dependendo do objetivo final do *demi-plié*. O tamanho do efeito foi alto para cada músculo, mas pequeno quando comparado em conjunto para cada condição experimental. Diferenças significativas prevaleceram entre os *demi-pliés* na preparação de movimentos complexos, como saltos e voltas. Os espectrogramas wavelet mostram padrões distintos de ativação cerebral para todas as condições experimentais.

Discussão: Os bailarinos clássicos podem aprender vários padrões de execução do *demi-plié* quando se trata de executar movimentos subsequentes de ballet. O *demi-plié* que antecede os saltos exige forças pliométricas e possui planejamento motor em malha aberta necessitando de aceleração, enquanto o *demi-plié* simples é um circuito fechado, contando com atualização proprioceptiva. As diferenças na ativação muscular durante o *demi-plié* que antecede outros movimentos de ballet parecem ocorrer devido à antecipação estratégica que prevê o próximo movimento. O córtex sensório-motor parece exibir diferentes ordens de ativação dependendo do objetivo final do *demi-plié*. Apesar das diferenças nos padrões de coordenação, alguns *demi-pliés* são mais semelhantes que outros. Presumimos que o nível de complexidade do movimento de ballet desempenha um papel importante na realização de ajustes antecipatórios na coordenação do *demi-plié*.

Palavras-chaves: padrão de coordenação; ativação cerebral; padrão muscular de ativação; ballet clássico; *demi-plié*

CHAPTER 1:

General Introduction

1.1 INTRODUCTION

In human movement, coordination refers to the organization of motor system degrees of freedom (DOF). Bernstein (1967) posited that coordination is achieved by grouping DOF to form units of control that are functionally specific, termed synergies.

Human movement skills as classical ballet require coordination at three levels of analysis: i) muscular coordination, ii) interlimb coordination and, iii) coordination between brain and behavior (Kelso 1995; Kelso et al. 2018). Debaere and colleagues (2001) report that coordination is not managed by a specific brain area, yet it requires a general increase in the activation of a complete motor network that is distributed across cortical and subcortical regions. Changing the task goal may change brain dynamics and consequently interlimb coordination, leading to changes in coordination patterns.

A basic coordinated movement in classical ballet is the *demi-plié*, which can be defined as a smooth, continuous bending of the knees until just below the hips, while maintaining turnout at the hip joints, allowing the thighs and knees to be directly above the toes line whereas the heels remain on the floor (Coker et al. 2015; Imura & Iino 2016; Kim & Kim 2016). The *demi-plié* movement consists of two phases: descending phase and ascending phase. During the descending phase, the dancer lowers their body by flexing their knees and ankle joints simultaneously, with external rotation of the hips, while maintaining heels on the floor and minimum pelvic tilt with an upright posture. The descending phase is critical for developing lower limb strength, as it requires the activation of several muscles at the same time. The ascending phase of the *demi-plié* is initiated by the upward movement of the pelvis, which extends the thighs, knees and ankle joints simultaneously. The muscles of the lower limb work to accelerate the upward movement and control the ascent. The ascending phase is often in preparation for subsequent muscles.

Even though the *demi-plié* is relevant to perform other dance movements, there is little scientific description of the *demi-plié* movement at the kinematic and muscular activity level (Trepman et al. 1994; Gontijo et al. 2015; Coker et al. 2015; Couillandre et al. 2008), and no scientific description of cortical brain activation. The description of the *demi-plié* at any of these levels can provide information to better understand coordination patterns while performing this basic ballet movement, raising research questions as:

- Is motor coordination required to perform a *demi-plié* affected due to changes in the task goal?
- During the performance of a *demi-plié* are there different muscular patterns of activation related to different end-goals?
- Is it possible to characterize differences in brain cortical activation when the *demi-plié* has a different end-goal?

Being more specific, how does the coordination at muscular, interlimb and brain cortical activation level change when the *demi-plié* is coupled with other ballet movements such as a jump or a turn?

Aiming to answer these questions, we analyzed the *demi-plié* itself and linked with four other ballet movements: *demi-plié* in preparation for heel rises (i.e., *relevé*), *demi-plié* in preparation for vertical jumps (i.e., *sauté*), *demi-plié* in preparation for lateral displacement of the body (i.e., *sissonne fermée de côté*), and *demi-plié* in preparation for turning outward (i.e., *pirouette en dehors*). We hypothesized that different movements associated with *demi-plié* would show differences at interlimb, muscular, and brain cortical activation level.

To illustrate, both *sauté* and *pirouette en dehors* begin with a *demi-plié*, however, they clearly differ in goals. A *sauté* has the goal to achieve the highest height, whereas a *pirouette en dehors* has the goal to perform a balanced and fluid pivot in one leg. These different task goals may lead to differences in the coordination of the *demi-plié* at all levels of organization. For instance, Coker and colleagues (2015) explain that the *demi-plié* and the *sauté* are foundational movements in classical ballet, but with differences in their sensorimotor planning requirements. The *demi-plié* is a closed-loop movement that relies on proprioceptive updating, whereas the *sauté* is a ballistic movement that is more typical of open-looping planning.

In summary, the aim of the present dissertation is to demonstrate that the apparent same *demi-plié* with different task goals, require specific modes of coordination expressed by differences on kinematic, muscular and brain activation.

1.2 OBJECTIVES

The present dissertation is divided into five studies.

The **first study** was of our interest to better understand what had been done in science in terms of utilized tools to measure ballet movements. Due to that, we designed a systematic review (Quadrado et al. 2022) as part of the present dissertation, in order to compile all the sensing technology used to capture ballet movements, as well as to list which ballet movements have been studied so far and what type of ballerinas were the main subjects of analysis. A detailed description of the systematic review is in Chapter 4. The systematic review guided us in developing the methodology applied in this research, selecting the sensing technology to capture the *demi-plié* data and the subsequent ballet movements through techniques such as motion capture to analyze movement kinematics, electromyography (EMG) to analyze muscular activation, and electroencephalography (EEG) to analyze brain cortical activation.

The **second** and **third studies** aimed to describe the *demi-plié* movement at the kinematic level, seeking to find possible dissimilarities in the vertical hip movement trajectory, and possibly distinguish differences in coordination patterns when the *demi-plié* has different end-goals. In other words, how lower limbs and knees joints adjust to each other to perform a coordinated movement, resulting in a fine motor control that leads to smooth transitions between movements, thus creating aesthetic beauty as seen in ballet movements.

The **fourth study** aimed to identify possible differences in muscular patterns of activation when the *demi-plié* has a different end-goal, as well as to analyze muscular activation in both descending and ascending phases of the simple *demi-plié* movement and when it is in preparation for subsequent ballet movements.

The **fifth study** aimed to analyze the brain dynamics of the sensorimotor cortex (i.e., the primary motor cortex ‘M1’, premotor cortex ‘PMC’ and supplementary motor area ‘SMA’), analyzing the frequency bands alpha (8-13 Hz), low-beta (13-18 Hz), and high-beta (18-30 Hz), as it has been well documented that these frequency bands of oscillatory activity show coherence with motor control (Ushiyama et al. 2010). To the best of our knowledge, there are no previous studies regarding brain cortical activation in ballet movements. Previous research is strictly related to visual and kinesthetic imagery, giving us insights about the areas of the brain involved during imagery of motor actions but not during the performance of ballet movements.

1.3 DISSERTATION STRUCTURE

This chapter explains the research questions that we previously addressed and outlined, and how we intended to accomplish our goals. Chapter 2 explores relevant literature and identification of gaps in the field of ballet research that were addressed by this research.

Chapter 3 establishes the research design for the five studies. It details data collection methods and analysis, and the selection of participants to perform the experiments. The following Chapters 4 through 8 compile the scientific articles produced throughout the PhD program in order to answer the research questions and confirm or refuse hypotheses. To the date, we have two studies already published (article 1 and 2), and three other studies (articles 4, 4 and 5) under peer-review. All submitted articles were in Q1 journals with established ISI Impact Factor or SCImago journal rank.

Chapter 9 describes a general discussion and conclusions by summarizing the findings from the substantive chapters and synthesizing them to outline potential limitations to this research, as well as to elaborate the development of future research in classical ballet. It discusses how this research contributes to existing knowledge and provides new insights about coordination during the *demi-plié* movement.

References used in the dissertation are presented at the end of Chapter 9, adopting alphabetic order.

References used for the scientific production of the five articles are listed at the end of their respective chapters (Chapters 4 through 8), adopting the format used upon submission to scientific journals.

Where used, ballet terminology and vocabulary are *italicized.*

CHAPTER 2:

Literature Review

2.1 CLASSICAL BALLET

It is widely known that ballet is complex and highly technical. Simply by watching it one gets a sense of the precision, detail and exactitude of ballet movement. Classical ballet as it is performed on stage by elite professionals is far removed from everyday movement and it requires years of dedicated training and development through formalized methods. Ballet is a highly codified system which possesses its own vocabulary that is governed by underlying principles such as turnout, line and coordination, as well as syntax which dictates how steps and movements are arranged into sequences according to the logic of the style (Bannerman 2014).

Ballet is explicitly taught through progressive sequences or exercises, which begin with simple movements and expand into more elaborate, complex movements as skill develops. For example, early levels of ballet training develop foundational positions in exercises that are relatively short and segmented in that they tend to focus on one or two particular steps in a very basic arrangement (Lambrinos 2019).

The literature in ballet is broad, ranging from popular manuals, guides and dictionaries of ballet aimed toward dancers and teachers (Foster 2010; Grant 2014; Kant 2007; Kneeland 2012; White 1996), to academic studies that explore how dance develops particular identities (Pickard 2013, 2015; Sumanapala et al. 2018; Wulff 1998) and scientific knowledge regarding motor behavior and biomechanics (Gontijo et al. 2015; Gorwa et al. 2020; Imura & Iino 2016, 2018; Lott 2019; Lott & Xu 2020; Wyon et al. 2013), elucidating aspects of movement performance by providing frameworks of the ballerina body and ballet movements. In particular, since the early 1960s, literature shows research approaches regarding movement performance of the human body from the dance perspective.

Scientific research in classical ballet has evolved in the past decades. Several literatures and systematic reviews have been published in the past decade on the topic of classical ballet, some of them addressing issues such as injuries and rehabilitation processes, finding and compiling techniques that may help dancers to prevent injuries or to recover from them (Letton et al. 2020; Smith et al. 2015; Storm et al. 2018 Trentacosta et al. 2017), and others regarding motor behavior and biomechanics analysis associated with ballet (Chang et al. 2016; Krasnow et al. 2011; Rangel et al. 2020; Yan et al. 2011). Research regarding brain cortical activation has been done from the perspective of motor imagery and associations, some using functional magnetic resonance image (fMRI) (Abraham et al 2016, 2019; Calvo-Merino et al. 2005; Golomer et al. 2008, 2009; Miller et al. 2010), and others using EEG (Angelopoulou et al. 2023; Di Nota et al. 2017; Gonzalez-Rosa et al. 2015; Orlandi et al. 2020) To the best of our knowledge, there are no studies to this date analyzing brain cortical activation during the performance of a ballet movement, using tools such as EEG.

2.1.1 The demi-plié movement

When starting ballet training, one of the first movements the ballet dancer learns is the *plié*, which in French means “bent”. This basic movement is used in jumps and turns to provide spring, absorb shock, and as an exercise to loosen muscles and to develop balance (Imura & Iino 2016). Performed in all of the five basic foot positions of classical ballet (Gorwa et al. 2020), *pliés* may be shallow, so that the heels of the ballet dancer remain on the floor (i.e., *demi-plié*), or deep, so that in all foot positions (except the second position) the heels rise (i.e., *grand-plié*). The *plié* movement is not only considered a basic movement, but also the mental foundation of ballet, as it is used to begin almost all ballet movements.

Pliés are used to prepare the ballerina body to open the pelvis and facilitate lateral rotation of the lower limb (turnout), as well as to strengthen and lengthen the abductors muscles. *Pliés* are also used to build strength in the hamstring muscle, to stretch the Achilles tendon, and distribute the energy throughout the metatarsals (Gontijo et al. 2015). Far from being simple, ballet schools teach the *plié* movement along the course of eight years, always beginning the routines of classes with sequences of exercises for *demi-plié* and *grand-plié*, both in the barre and in the center, which is a common structure of a ballet class. For beginners, the didactic used to teach the *plié* movement takes into consideration the control of the pelvis, avoiding forward rotation in an anterior tilt as a result of the rectus femoris action (Couillandre et al. 2008), as the dancer must avoid hyper lordosis, abdominal protrusion and anterior shoulder position. For the professional dancer, the *plié* is performed in several combinations with other ballet steps and positions, often used to warm up the body and maintain pelvic and lower limb flexibility acquired throughout years of training.

Despite its artistic importance and apparent simplicity, anecdotal evidence suggests that 95% of dancers do not perform *pliés* correctly, while many dancers, teachers, and health professionals remain surprisingly unaware of the biomechanics and anatomy of this primary and fundamental movement (Couillandre et al. 2008). In terms of research, the *demi-plié* has so far attracted some scientific attention, aiming to describe the kinematics of the *demi-plié* (Gontijo et al. 2015), muscles in the lower limb involved in the *demi-plié* (Trepman et al 1994; Couillandre et al. 2008), and pelvic stability of the *demi-plié* (Coker et al. 2015).

The *demi-plié* movement is known for presenting two distinct phases; descending and ascending. The descending phase demands great external rotation (turnout) of the hip joints, as well as fine alignment between the knees and the toes, relying on the minimum pelvic tilt for stabilization of the posture and balance. Classical ballerinas present greater turnout of the hips, hence more technique to perform *demi-plié* in comparison to modern dancers (Trepman et al. 1994). Conversely, the ascending phase of this movement is often in preparation for a subsequent movement such as a jump, a turn or a body displacement in space, so it will require postural adjustments and differences in ground reaction forces in order to get the necessary impulse and mechanics for next steps. Muscular activation will also vary in the descending and ascending phases, as the *demi-plié* is a plyometric movement and it will work respecting agonist-antagonist muscle function activation. For instance, it has been described that the tibialis anterior is active only during the descending phase, for both classical and modern dancers, and the vastus lateralis and medialis behave similarly to each other, with increase in the end of the descending phase, followed by decreasing activity as the ascending phase begins (Trepman et al. 1994).

The presence or absence of muscular activity in each phase of the *demi-plié* is important to characterize the muscle use during this movement. Previous research has shown significant differences in muscle activation between classical and modern dancers depending on the phase of the *demi-plié*. Trepman and colleagues (1994) described that the *demi-plié* is often initiated with little or no lower extremity EMG activity. As the *demi-plié* progresses, knee flexion in the descending phase, stabilization at midcycle, and extension during the ascending phase all appear to be actively controlled by the quadriceps muscles, as previously observed in non-dancers performing a squat movement (Basmajian et al. 1972).

2.2 COORDINATION PATTERNS OF BALLET MOVEMENTS

Coordination patterns in classical ballet have been studied and linked to various aspects of ballet performance and training. Previous research has explored how coordination patterns are manifested in motor behavior and brain activity, emphasizing their importance in the neural and physical aspects of ballet.

Kelso and colleagues (2018) demonstrated a significant link between physical movement patterns and brain activity in dancers, highlighting that coordination patterns observed in a ballet dancer’s behavior are also mirrored in their brain signals. Such findings suggested that the study of movement coordination in ballet can serve as a valuable tool for probing and understanding the brain functions in individual subjects. It emphasizes the potential of using ballet as a medium to explore broader neurophysiological concepts, revealing how intricately the brain and body are connected in the context of complex and coordinated movements, such as those required in classical ballet. Years of ballet training are shown to alter how the central nervous system (CNS) coordinates muscle movements for walking and balancing. This adaptation indicates a profound restructuring of the modular organization of balance control in response to the rigorous demands of ballet technique (Sawers et al. 2015).

In another study on multi-segmental postural coordination in professional ballet dancers, Kiefer and colleagues (2011) observed that the coordination patterns depend on various parameters of the motor action goals, such as frequency and amplitude. The authors found that ballet dancers exhibit increased coordination stability, possibly due to enhanced neuromuscular control or perceptual sensitivity. This stability is important for dancers to perform complex balance tasks, indicating a high level of proficiency in managing the constraints of ballet movements.

Classical ballet technique requires specific motor actions that demand precise spatial and temporal coordination of multi-joint limb movements along with postural control. High levels of postural control are paramount for ballet dancers to achieve an optimal aesthetic level in their performances, as well as it plays a role in reducing the risk of musculoskeletal injuries. The exceptional postural control observed in ballet dancers is a direct outcome of the intricate coordination patterns they master (Janura et al. 2019). These patterns, refined through rigorous training, enable dancers to maintain balance and control over their movements, demonstrating the importance of coordination in both the artistry and the safety aspects of ballet technique.

CHAPTER 3:

Research Design

3.1 SELECTION OF PARTICIPANTS

Participants were 13 classical ballet dancers (10 females, 3 males), ages ranging between 20 to 45 years old, with at least 6 years of experience in classical ballet and currently active in the modality. The sample size was determined using F-tests (ANOVA, Repeated Measures, Within Factors) for 1 group and 5 measurements, a medium effect size of 0.25, an alpha error probability of 0.05, a beta error probability of 0.20, and a correlation amongst repeated measures of 0.75, which provided a total sample size of 12 subjects. This procedure was performed using the GPower software (version 3.1.9.7, Universität Düsseldorf, Germany).

Demographics of the participants varied between college students, characterized as pre-professional dancers, professionals, currently working in professional dance companies, and amateurs, characterized as practicing ballet classes as hobby or for leisure (for detailed information, see Table 1 displayed in Chapters 5 through 8). All participants have signed an informed consent for voluntary participation in the experiments (please see Appendix A), and answered questionnaires regarding ballet experience, injuries, and demographics (please see Appendix B). Participants were healthy subjects and have not presented with any sort of injury within 6 months prior to the experiment date.

The research was approved by the Ethical Committee of the Faculty of Human Kinetics, University of Lisbon, (protocol number 32/2020) in accordance with the latest version of the Declaration of Helsinki for experiments in humans.

3.2 DATA COLLECTION

The kinematic analysis room contained eight infra-red cameras (Optitrack Prime 13), with sample rate at 100 Hz, and displayed in the umbrella formation. The room had linoleum flooring, commonly used in ballet classes and theater stages, and dimmed lighting to avoid interference or distraction.

EMG data was recorded using two portable devices (BITalino MuscleBIT, Plux Biosignals) (Batista et a. 2014), one for each leg, attached to a small pouch placed around the waistline of the participants. Each device had four channels, each connected to a twined cable and snap buttons for pairs of surface disposable electrodes (Ag/AgCl). Electrode pairs were placed in a bipolar configuration along the longitudinal axis and belly of the selected muscles: tibialis anterior (TA); gastrocnemius medialis (GM); rectus femoris (RF); and long head of the biceps femoris (BF), bilaterally for all the participants. The inter-electrode distance was 1.5 cm. The correct placement was confirmed by manual muscle testing performed by an experienced researcher, and visual inspection of the raw EMG signal by the experimenter. The ground electrode was placed over the right lateral malleolus of all participants. The same researcher was responsible for the electrodes' placement in every participant. After familiarization, participants reported no serious impediment, of either electrodes or cables, in performing the referred ballet movements. The EMG devices were connected via Bluetooth to a computer, and data was captured at a sample rate frequency of 1000 Hz. Before placing the electrodes, skin was shaved when needed, cleaned with alcohol, and slightly abraded to further reduce skin resistance, in accordance with the SENIAM recommendations (Hermens et al. 2000).

After placement of the EMG apparatus, participants wore a non-reflective black suit, with four reflective spherical markers of 3 cm of diameter located bilaterally in the pelvis to characterize the position of the posterior superior iliac spine (PSIS) and anterior superior iliac spine (ASIS), as well as four sets of three reflective markers, located bilaterally in the outer thighs and shanks to characterize the knees joint angles based on lower limbs segments relative angles, respecting the Calibration Anatomic System Technique (CAST) method for motion capture (Cappozzo et al. 1995). Participants wore soft ballet shoes, regularly used in ballet training. A metronome was set at 64 bpm to encompass the rhythm and cadence of the *demi-plié* movement.

Brain cortical activity was captured through EEG technique (ENOBIO® EEG Systems, Neuroeletrics), with 8 channels and sample rate frequency of 500 Hz, for the respective motor areas: C3, C1, Cz, C2, C4, F3, Fz, and F4. The dry electrodes were placed according to the 10-10 international system, offering more localized measurements (for detailed information, see Koessler et al. 2009), using a carefully positioned nylon cap (Figure 1). These values refer to the distances between electrodes in relation to the total cap size (i.e., 20% of the total distance from the inion to the nasion) and aim to provide consistency across experiments. Electrodes were placed on the head of the participants with reference to anatomical landmarks such as the inion, nasion, and left and right pre-auricular points, such that the central electrode Cz is approximately aligned with the vertex (Scrivener and Reader, 2022).

The source location of each channel was chosen based on its brain functional representation related to motor control and voluntary lower limb action. The M1, PMC, and SMA are important components of the brain's cerebral cortex, each associated with distinct gyri and collectively involved in the control and execution of movements (Koessler et al. 2009; Scrivener and Reader, 2022).

The M1, which is essential for executing movements, is located in the Precentral Gyrus, directly anterior to the central sulcus. This area is important for the direct control of voluntary muscle movements, particularly fine motor movements (Koessler et al. 2009; Scrivener and Reader, 2022; Heed and Röder, 2010; Cui et al. 2019). The specific electrodes relevant for capturing M1 activity are C3, Cz, and C4. These are strategically positioned to monitor the left hemisphere (C3), the midline (Cz), and the right hemisphere (C4), respectively. In the more detailed 10-10 system, electrodes C1 and C2 provide finer resolution for M1 activity. C1 is located over the left hemisphere and C2 over the right, both positioned slightly off the midline. These electrodes are instrumental in capturing neural signals related to voluntary muscle movements of the lower limbs, according to the homunculus representation, especially fine motor actions (Koessler et al. 2009; Scrivener and Reader, 2022; Heed and Röder, 2010; Cui et al. 2019).

The PMC, situated in the frontal lobe, primarily involves the Precentral Gyrus, vital for initiating voluntary movements, and extends into the Superior and Middle Frontal Gyri for more complex planning (Koessler et al. 2009; Scrivener and Reader, 2022; Heed and Röder, 2010). The relevant electrodes for monitoring PMC activity include F3, Fz, F4, C3, Cz, and C4, combining both the frontal and central regions (Heed and Röder, 2010; Cui et al. 2019). These electrodes help in capturing the neural dynamics involved in the planning and preparation stages of voluntary movements.

In addition, the SMA, located on the medial surface of the frontal lobe, is predominantly found in the Medial Frontal Gyrus, extending into the Paracentral Lobule and occasionally the Superior Frontal Gyrus, playing a key role in planning and coordinating complex, internally generated movements. The most relevant electrodes for SMA activity are Fz and Cz. These midline electrodes are effective in capturing activity of the SMA due to its medial location. Additionally, electrodes C1 and C2 from the 10-10 system, while more directly over the M1, can also pick up some activity from the SMA. This is due to the adjacency of these areas, allowing for the capture of some SMA-related signals, although with less specificity than the midline electrodes (Koessler et al. 2009; Scrivener and Reader, 2022; Heed and Röder, 2010; Cui et al. 2019).

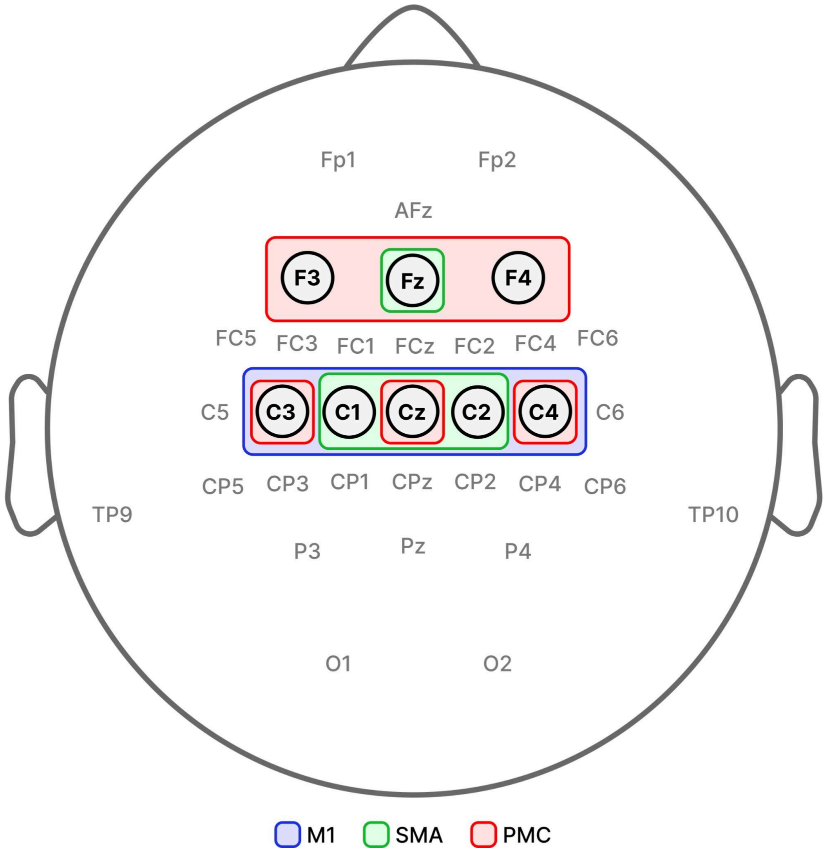

Figure 1: Brain cortical location for each of the 8 electroencephalography dry electrodes placed on the scalp of all the participants in a nylon cap. C3, C1, Cz, C2, and C4 capture cortical activity from the M1 (primary motor area); C1, Cz, C2, and Fz capture cortical activity from the SMA (supplementary motor area), and; C3, Cz, C4, F3, Fz and F4 capture cortical activity from the PMC (premotor cortex area).

3.3 EXPERIMENTAL DESIGN

Participants performed the *demi-plié* and the *demi-plié* prior to four subsequent movements, such as: *relevé*, *sauté*, *sissonne fermée de côté* and *pirouette en dehors*. Participants were allowed to choose their preferred side to perform the *pirouette* revolution, as well as the lateral body displacement in the *sissonne*. The order of ballet movements was randomly selected for each participant, all performed in the “first position” of classical ballet for both feet and arms (Figure 2). Participants wore soft ballet shoes, regularly used in ballet training, and had warmed up prior to measurements and testing.

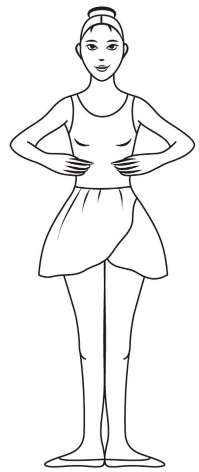

Figure 2: Illustration of the first position for both feet and arms, commonly performed in classical ballet. Image granted from Artsashina with permission for educational and non-commercial use.

The metronome configured at 64 bpm set the cadence of the descending phase of the *demi-plié*, clearly verbalized by the experimenter to perform the descending phase in 2 beats, to prepare for the ascending phase that would be fused to the subsequent ballet movement. For the performance of the simple *demi-plié*, participants were instructed to also perform the ascending phase in 2 beats of the metronome.

Participants performed five repetitions of each experimental condition, with varied interval time between repetitions, in order stabilize the EEG signal after the landing of the *sauté*, *sissonne fermée de côté*, and *pirouette en dehors*. For the simple *demi-plié* and *relevé*, which did not present any impact in the final performance, therefore not presenting destabilization of the EEG signal, we followed a protocol of 4 beats of the metronome as intervals between repetitions. The pilot trial showed that five repetitions would be the optimum amount in order to avoid muscular fatigue, as the participants would have to perform five different experimental conditions in only one experimental session. The interval between experimental conditions was set at 5 minutes of rest for all the participants, or for as long as it would take for the EEG signal to stabilize. The total time of the experiment session was approximately 1 hour.

3.4 DATA ANALYSIS

3.4.1 Isolating the demi-plié from the subsequent ballet movements

Since our goal was to identify possible dissimilarities in the trajectory of the *demi-plié*, as well as to possibly distinguish different coordination patterns and brain cortical activation during this movement in its different end-goals, it was necessary to select the data that only contained information about the *demi-plié* (i.e., the descending and ascending phases only). Hence, the data analysis of all sensing technology used in our experiments had to undergo this procedure.

3.4.1.1 Kinematic analysis

In regards to the kinematic analysis, which involved analyzing the data captured from the motion capture technique, the descending and ascending phases of the *demi-plié* were characterized based on the Y-coordinate values relative to the hip vertical trajectory, based on the reflective markers for the PSIS and ASIS. Specifically, the descending phase was identified as the period when the Y-coordinate values began to decrease and ended when the coordinate stabilized. Conversely, the ascending phase was identified as the period when the Y-coordinate values began to increase and ended when the trajectory accelerated to engage in the subsequent movement.

To do so, an in-house developed MATLAB routine was used (version R2022b, MathWorks Inc., USA). This routine provided time series data that exclusively contained the *demi-plié* movement of the five experimental conditions, enabling the selection of the appropriate phases for analysis. The data from the simple *demi-plié* movement were used as a model for selecting the corresponding phases for the other four movements.

3.4.1.2 Electromyography

The EMG signals were recorded using the OpenSignals software (Plux Biosginals), in which were identified the starting time of the descending phase of the *demi-plié*, and the end of the ascending phase, when the *demi-plié* would then be fused to the subsequent movement. The timing of muscle contraction was selected for both phases using the muscle activation pattern observed in the isolated *demi-plié* performance as the reference. As the metronome was set at 64 bpm, the time of execution of the *demi-plié* was two beats of the metronome for the descending phase, and two beats for the ascending phase, then linked to the subsequent movement. However, depending on the subsequent movement, muscle activation could differ, possibly in anticipation for the next movement, so the ascending phase was limited based on the time set by the metronome, which often coincided with the deactivation of the TA in the ascending phase, as observed in the isolated *demi-plié*.

3.4.1.3 Electroencephalography

In regards to the EEG procedure, the data containing only the descending and ascending phases of the *demi-plié* was synchronized in the EEG software with the time that the participants initiated the *demi-plié* as preparation for the subsequent ballet movements (based on annotations made in real time by the experimenter), as well as compared to the signal pattern of the simple *demi-plié*, as a reference for the descending phase, and the beginning of the ascending phase, since the end of the ascending phase is fused to the next movement.

Mean calculation of the execution time regarding the beginning of the descending phase and end of the ascending phase of the *demi-plié* was performed, giving us the values of duration of the *demi-plié* that were further plotted for comparisons amongst experimental conditions.

A full description of the data analysis of each study is detailed in the subsequent chapters of the dissertation (chapters 4 through 8), relative to each scientific article produced for each study.

CHAPTER 4:

Scientific Production - Article 1

Sensing technology for assessing motor behavior in ballet:

A systematic review

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ABSTRACT

Background: Human performance in classical ballet is a research field of growing interest in the past decades. Technology used to acquire data in human movement sciences has evolved, and is specifically being applied to evaluate ballet movements to better understand dancers' profiles. We aimed to systematically review sensing technologies that were used to extract data from dancers, in order to improve knowledge regarding the performance of ballet movements through quantification.

Methods: PubMed, MEDLINE, EMBASE, and Web of Science databases were accessed through 2020. All studies that used motor control tools to evaluate classical ballet movements, and possible comparisons to other types of dance and sports movements were selected. Pertinent data were filled into a customized table, and risk of bias was carefully analyzed.

Results: Eighty studies were included. The majority were regarding classical ballet and with pre-professional dancers. Forty-four studies (55%) used two or more types of technology to collect data, showing that motion capture technique, force plates, electromyography, and inertial sensors are the most frequent ways to evaluate ballet movements.

Discussion: Research to evaluate ballet movements varies greatly considering study design and specific intervention characteristics. Combining two or more types of technology may increase data reliability and optimize the characterization of ballet movements. A lack of studies addressing muscle–brain interaction in dancers were observed, and given the potential of novel insights, further studies in this field are warranted. Finally, using quantitative tools opens the perspective of defining what is considered an elite dancer.

Keywords: sensing technology; motor behavior; human performance; ballet; dance

4.1 BACKGROUND

Motor behavior in dance has been a field of growing interest in the past decades. In particular, since the early 1960s, literature shows research approaches regarding movement performance of the human body from the dance perspective [1].

In 2009, a literature review was published regarding biomechanics measurement tools used in dance [2]. The authors reviewed and analyzed studies concerning selected ballet movements, measurement tools, research design, participants' characteristics, and type of study. In the meantime, the number of studies in the past ten years has substantially increased, not only considering the increased demand for dance research, but especially due to the evolution of digital technologies that have allowed researchers to collect exponentially more data with unprecedented accuracy. Thus, the present systematic review aims to update the literature with all the findings made throughout the years regarding studies in motor behavior in ballet, especially focusing on the digital sensing technologies used. This systematic review offers then not only an updated description concerning measurement tools and data collection in dance, but also the ballet movements of interest and trends of study, identifying future potential avenues for research.

For additional context, several literature and systematic reviews have been published in the past decade on the topic of classical ballet, but mostly addressing issues such as injuries and rehabilitation processes [3–6], finding and compiling techniques that may help dancers to prevent injuries or to recover from them. However, four systematic reviews were found regarding motor behavior and biomechanics analysis associated with dance [2,7–9]. By studying isolated parts of the body or analyzing a specific movement, researchers reviewed studies in order to understand what has been explored in the dance feld and what is still to be discovered. Herein, the present systematic review aims instead to explore which digital sensing technologies have been used to capture data specifically from ballet movements. Finally, ballet research has also captured the interest of neuroscientists, aiming to understand the brain mechanisms involved in dance, as well as the mechanisms that could possibly differentiate elite dancers from novices, through systematic reviews that analyzed mental imagery and cortical activity during imagery tasks [10–12]. In the present review only those digital technologies addressing these latter topics were the object of our research.

4.2 METHODS

This systematic review conforms to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement [13] and has been registered in the International Prospective Register of Systematic Reviews (PROSPERO, protocol no. CRD42020206680) [14].

Four database search engines (PubMed, MEDLINE, EMBASE, and Web of Science) were used to identify eligible scientific articles regarding human performance and motor behavior in ballet and dance (i.e., contemporary dance and modern dance), sensing technology, and instruments and tools for data capture in dance. The search encompassed literature published until December 2020, with headings and keywords related to motor behavior in ballet ((classical ballet OR dancing OR elite dancers) AND (randomized controlled trials OR RCT OR quasi-RCT); (classical ballet OR classical dancing OR classical dance OR ballet OR elite dancers) AND (biomechanics OR biomechanical tools OR biomechanics instruments OR biomechanics analysis); (ballet movements OR ballet positions OR dance movements OR elite dancers) AND (measurement tools OR sensing technology OR motor behavior OR human performance); (EMG OR sEMG OR electromyography OR surface electromyography OR muscle activity) AND (classical ballet OR classical dance OR classical dancing OR ballet movement OR dance movement OR elite dancers); (GRF OR ground force reaction OR kinetic analysis) AND (classical ballet OR classical dance OR classical dancing OR ballet movement

OR dance movement OR elite dancers); (motion capture OR kinematic analysis OR motion analysis) AND (classical ballet OR classical dance OR classical dancing OR ballet movement OR dance movement OR elite dancers); (accelerometer OR inertial sensor OR inertial sensors) AND (classical ballet OR classical dance OR classical dancing OR ballet movement OR dance movement OR elite dancers); (EEG OR electroencephalography) AND (classical ballet OR classical dance OR classical dancing OR ballet movement OR dance movement OR elite dancers)), and disregarding articles related to injury evaluation, rehabilitation purposes, and neurological disorders.

4.2.1 Inclusion and Exclusion Criteria

Inclusion criteria were defined by type of dance, participants, and research tools. Studies that evaluated classical ballet movements and possible comparisons to other types of dance and sports were included. Participants of those studies were regarded as classical, modern, and contemporary dancers. Articles involving tools such as 3D cameras, motion capture, laser sensors, video analysis, cinematography analysis, inverse dynamic analysis, image reconstruction, force plates, seesaw plates, dynamometers, accelerometers, inertial sensors, and surface EMG (sEMG) were included in our search. We considered studies without language restrictions; however, all the selected articles were published in English.

As exclusion criteria, articles containing only abstract, conference proceedings, systematic reviews, and other types of literature review and studies conducted involving older adults and with purposes of rehabilitation treatment were excluded. Articles involving manual measurement through analog tools (i.e., goniometers and/or measurement tapes), magnetic resonance imaging (MRI), X-rays, and ultrasound as isolated techniques of analysis were also excluded.

4.2.2 Data Management

One of the authors screened the titles and abstracts of all identified studies according to the selection criteria. Full texts were then retrieved. Two other authors independently extracted the data and reached consensus, filling a designed table to extract pertinent data. The ROBINS scale [15] was applied to analyze risk of bias, because most of the retrieved articles were non-randomized controlled trials (RCT). For the RCT studies, risk of bias was analyzed through the Cochrane Collaboration's tool [16].

4.3 RESULTS

4.3.1 Literature Search

The database search process retrieved 2632 potentially relevant articles. References of the included articles were then scanned to ensure that relevant literature was not excluded from the review, and 12 additional records were identified. After duplicates were removed, the number of articles decreased to 1619. Articles were screened first by title and abstract for relevance to ballet, motor control sensing technology tools, and finally by full text (n=116 full texts were assessed for eligibility) using the inclusion and exclusion criteria. After the evaluation process, 80 studies met the inclusion criteria. Articles were not limited by year of publication; however, the earliest article found regarding our search terms was published in 1993. We included articles published throughout the years until December 2020 (Figure 1).

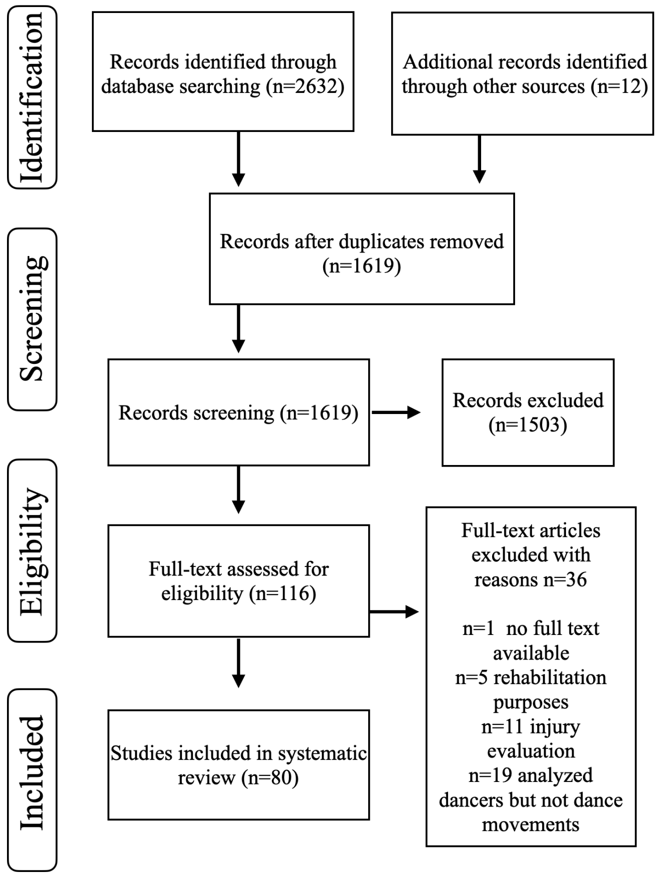

Figure 1: Diagram of information through the different phases in the systematic review

4.3.2 Quality Index

Regarding the 80 studies included in the present systematic review, only 3 studies were RCT, and their risk of bias were analyzed through the Cochrane Collaboration's tool for assessing risk of bias [16-18]. The 3 studies showed the same outcome, as high risk in 4 out of the 7 analyzed variables as described "random sequence generation", "allocation concealment"; "blinding of participants and personnel"; "blinding of outcome assessment", and low risk for the variables "incomplete outcome data"; "selective reporting", and; "other sources of bias". The remaining 77 studies were then analyzed through the ROBINS scale [15], and the obtained scores were 3 studies presenting low risk of bias, 37 studies low to moderate, 21 studies moderate, 8 studies moderate to serious, and 8 studies presenting serious risk of bias. Please see Table 1 for detailed description.

The United States is the leading country of publications (26 articles), followed by France (11 articles), Australia (10 articles), Japan (8 articles), Taiwan (7 articles), United Kingdom (5 articles), Brazil and Poland with 3 articles each country, Switzerland (2 articles), Colombia, Canada, Spain, Czech Republic, and Israel with 1 article per country. Ballet research has increased in the past decade (Figure 2). Between the years of 1993 and 2004, there were few publications regarding motor control in ballet, although numerous articles were found associating ballet to injury and rehabilitation processes.

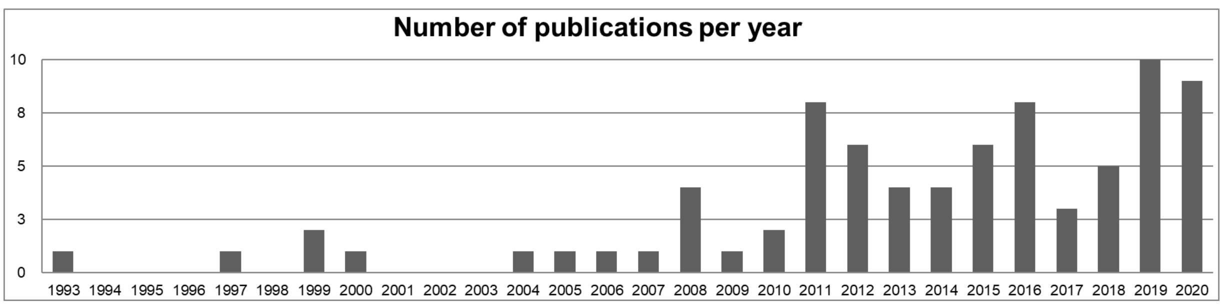

Figure 2: Yearly publications regarding studies of motor control in ballet (1993 – 2020)

4.3.3 Category of Dance and Level of Expertise

Regarding the 80 articles included in the present systematic review, 60 studies have analyzed participants specifically from classical ballet; 14 have combined participants from classical ballet and modern dance, and; 6 studies have analyzed participants from contemporary dance.

Thirty-nine studies analyzed and described ballet movements, without running any sort of comparisons between groups of participants regarding experimental conditions. These studies were divided as: i) 25 studies with participants from classical ballet; ii) 9 studies with participants from modern dance; and iii) 5 studies with participants from contemporary dance. Concerning the participants level of expertise, 11 out of the 39 studies recruited elite dancers as participants, 22 studies recruited pre-professionals, and 4 had elite dancers and pre-professionals within the same study (but without comparisons between levels of expertise). Two studies did not mention the level of expertise.

Forty-one studies have compared groups of the experimental design, with 14 studies comparing dancers to non-dancers (10 studies compared elite dancers to non-dancers), 5 compared elite to novices, 3 studies compared elite to pre-professionals to novices, and 1 study compared elite to pre-professionals. Six studies compared males to females. Four studies compared injured dancers to non-injured (one study did not mention the level of expertise but also compared injured to non-injured). According to the category of dance, 2 studies compared classical ballet to modern dance. Regarding practice conditions, 3 studies compared different types of shoes, and 2 studies compared the condition of barefoot to wearing shoes. The remaining studies compared different groups under different experimental conditions. Twenty studies analyzed elite dancers, 19 analyzed pre-professionals, and 7 analyzed novices, considering that some of the studies combined different levels of expertise without comparing them, yet analyzing other variables, such as gender and different tasks. Only 1 study compared elite dancers with non-dancers and acrobats.

4.3.4 Demographic Information

Three studies did not provide demographic information regarding participants' age, years of practice, and hours of weekly training. Only 16 studies have provided all demographic information. Fifty-two out of 80 studies had only female participants, 22 had both males and females, 2 had only males, and 4 studies have not mentioned participants' sex (Table 1).

Table 1: Participants characteristics, sensing technologies, category of movement, and risk of bias obtained from the studies included in this review. Abbreviations used in the EMG column: ES = *erector spinae*; RA = *rectus abdominis*; GM = *gluteus maximus*; Gm = *gluteus medius*; SAR = *sartorius*; BF = *biceps femoris*; SEM = *semitendinosus*; SM = *semimembranosus* ADL = *adductor longus*; AD = *adductors*; P = *psoas*; RF = *rectus femoris*; VL = *vastus lateralis*; VM = *vastus medialis*; VMO = *vastus medialis obliquus*; LGAS = *lateral gastrocnemius*; MGAS = *medial gastrocnemius*; SOL = *soleus*; TA = *tibialis anterior*; FIB = *fibularis longus*; EDL = *extensor digitorum longus*; FHB = *flexor hallucis brevis*; CP = classical ballet feet position (varying from 1 to 6).

Study	Participants	Category of dance	Sensing Technology	Ballet movement	Comparison between groups	Risk of bias
19. Weighart et al., 2020	Pre-professional; Age: 20 .3±1.4; H/w: 16.4 ± 9.0 Female	Classical ballet and modern dance	Isokinetic dynamometer; EMG: VMO, VL (right leg)	Demi-plié & sauté in CP1, CP6	ballet vs. modern / injured vs. non-injured	Low to moderate
20. Lott & Xu, 2020	Pre-professional & Elite; years of training: 20 Female	Classical ballet	Motion capture	En dehors pirouette in CP4	-	Low to moderate
21. Arnwine & Powell, 2020	Pre-professional & Elite; Age: F- 23.4±4.7, M - 27.4±4.4 Males & Females	Classical ballet	Force plates	Grand-jeté & sautés in CP1	Male vs. Female	Low to moderate
22. Jarvis et al., 2020	Elite; Age: 27.04±3.99; Years of training: 21.07±4.88 Female	Classical ballet	Motion capture; Force plates	Saut de chat from chassé	-	Low to moderate
23. Skopal et al., 2020	Pre-professional; Age: 19±2; Years of training: 9±5.3; H/w: 12 ± 12.5 Female	Contemporary dance	Motion capture; Isokinetic dynamometer	Grand-jeté	Dancers (extra-training) vs. dancers (regular training)	Low to moderate
24. Gorwa et al., 2020	Pre-professional; Age: Greater - 13.9±1.7, Lesser - 15.1±0.7; Years of training: Greater - 4.1±1.5, Lesser - 5.6±0.5 Female	Classical ballet	Motion capture; EMG: ES. RA, GM, SAR, BF, SEM, ADL, RF, VL, VM, LGAS, MGAS, TA, FIB	CP1 to 6	Greater hip turnout vs. lesser hip turnout	Low to moderate
25. Seki et al., 2020	Pre-professional; Age: 20; Years of training: 10 Female	Classical ballet	Motion capture	Demi-plié with hallux valgus in CP1	-	Low to moderate
26. Greenwell et al., 2020	Pre-professional; Age: 20.5 Males & Females	Classical ballet and modern dance	Motion capture	Grand-plié in CP1, CP5	-	Moderate to serious
27. Hendry et al., 2020	Pre-professional; Age: 19.6±1.2; H/w: At least 8 Female	Classical ballet and modern dance	Video analysis; Force plates; Inertial sensors	Sauté bilateral & unilateral	-	Low to moderate

Study	Participants	Category of dance	Sensing Technology	Ballet movement	Comparison between groups	Risk of bias
28. Janura et al., 2019	Elite; Age: F: 25.6±3.8 M: 23.4±4.0; Years of training: At least 10; H/w: 3 to 8 Males & Females	Classical ballet	Force plates	Postural sway	Elite vs. non-dancers	Moderate
29. Gorwa et al., 2019	Elite; Age: 28.6; Years of training: At least 9 Males & Females	Classical ballet and modern dance	Motion capture; Force plates	Grand-jeté, Entrelacé & Ballonné	-	Serious
30. Perry et al., 2019	Elite; Age: 20.7±2.7; Years of training: 13.9±5.0; Female	Classical ballet	Motion capture; Force plates	Saut de chat & temps levé	-	Low to moderate
31. Lin et al., 2019	Elite & Novices; Age: 17.8±3.4; years of training: for novices, 2-5 years and for advanced at least 6 years; H/w: 1.5-3h for novices, at least 3h for advanced; Female	Classical ballet	Motion capture; Force plates	En dehors pirouette in CP4	Elite vs. Novice	Moderate to serious
32. Lott, 2019	Pre-professional; Age: 16±1.4; Female	Classical ballet	Video analysis; Inverse dynamics	En dehors pirouette in CP4	-	Low
33. Blanco et al., 2019	Elite & pre-professional & Novices ; Age: 20.1±3.6; years of training: Novices: 1.3±0.9 Pre-professional: 3.4±1.4 Elite:7.2±2.4; Males & Females	Classical ballet	Motion capture; force plates; Inertial sensors	Grand-jeté	Elite vs. pre-professio nal vs. novice	Serious
34. Carter et al., 2019	Pre-professional; Age: 18.8±1.6; Years of training: 12.6±3.6; H/w: 19.5 ± 8.8; Female	Classical ballet and modern dance	Motion capture	Turnout of CP1 & sauté in CP1	-	Low to moderate
35. Aquino et al., 2019	Elite; Age: 22.2±2.2; Years of training: At least 10; Female	Classical ballet	Motion capture; Force plates; EMG: TA, MGAS (left leg)	Relevé in CP2 & piqué arabesque in CP4	-	Low to moderate
36. Mira et al., 2019	Elite & Novices; Age: Novices - 16.7±0.7, Elite - 23.5±1.5	Classical ballet	Motion capture; Force plates; EMG: MGAS, LGAS, SOL, VL	Cou-de-pied derrière with demi-plié to piqué arabesque	Elite vs. Novice dancers	Moderate
37. McPherson et al., 2019	Elite; Age: 19.28±1; Years of training: 12.85±2.37; H/w: 15.02 ± 7.49 ; Female	Classical ballet	Video analysis; Force plates	Grand-jeté & assemblé dessus from tendu devant	-	Low
38. Imura & Iino, 2018	Elite; Age: F – 1935, M – 28.3; Years of training: F – 14, M – 19.8; Males& Females	Classical ballet	Motion capture; Force plates	En dehors pirouette in CP4	-	Low to moderate

Study	Participants	Category of dance	Sensing Technology	Ballet movement	Comparison between groups	Risk of bias
39. Bruyneel et al., 2018	Pre-professional; Age: Young - 12.6±1.95, Adult - 22.4±5.06; Years of training: at least 4; H/w: Young - 14.4h ± 8.49, Adult - 23.8h ± 10.61; Males & Females	Classical ballet	Force Plates	Grand-plié in CP1	Young with adult dancers	Moderate
40. Bickle et al., 2018	Elite; Age: 26±4; Years of training: at least 3; H/w: at least 25; Female	Classical ballet	Video analysis; Force plates	Bourrés	Worn pointe shoes vs. new pointe shoes	RCT High Risk
41. Michalska et al., 2018	Elite; Age: 28.±7; Years of training: ; At least 5 with an average of 17; Female	Classical ballet	Force plates	Postural sway	Dancers vs. non-dancers	Moderate
42. Carter et al., 2018	Pre-professional; Age: 19.1±1.8; Years of training: 12.7±3.9; H/w: 19.9 ± 9.7; Female	Classical ballet and modern dance	Motion capture	Turnout of CP1 & sautés in CP1	-	Moderate
43. Carter et al., 2017	Pre-professional; Age: 18.8±0.8 ; Years of training: 11.7±3.1; Female	Classical ballet and modern dance	Motion capture	Demi-plié & elevé in CP1, degagé devant (flex-point-flex)	-	Moderate
44. Costa de Mello et al., 2017	Elite; Age: 28.4±10.8; Males & Females	Classical ballet	Force plates	Postural sway & retiré passé	Elite vs. non-dancers	Moderate
45. Saito et al., 2017	Pre-professional; Age: 20.3±1.6; Years of training: 16.8; H/w: 7.6; Female	Classical ballet	Force plates; EMG: SOL, MGAS	Elevé in CP6	Dancers vs. non-dancers	Low to moderate
46. Imura & Iino, 2016	Elite; Age: 30±1; Female	Classical ballet	Motion capture; Force plates	Sauté in CP1, CP6	-	Low to moderate
47. Jarvis & Kulig, 2016	Elite; Age: 27±3.9; Years of training: 20.8±4.9; Female	Classical ballet	Motion capture; Force plates	Saut de chat	-	Moderate
48. Hinton-Lewis et al., 2016	Pre-professional; Age: 19.2±1.3; Years of training: F - 5.2±4.1, M - 13.5±3.3; Males & Females	Classical ballet	Video analysis; Inertial sensors	Demi-plié, relevé & sauté in CP1	Male vs. Female	Moderate
49. Hopper et al., 2016	Pre-professional; Age: 19.2±1.3; Years of training: at least 5; Males & Females	Classical ballet	Motion capture	Demi-plié, battement fondu with elevé & relevé, ballonné en place, ballonné traveling & Sissonne fondu	-	Moderate
50. Quanbeck et al., 2016	Pre-professional & Elite; Age: 20.3±1.5; Years of training: 14.7±2.5; Female	Classical ballet and modern dance	Motion capture	Turnout of CP1	-	Low to moderate

Study	Participants	Category of dance	Sensing Technology	Ballet movement	Comparison between groups	Risk of bias
51. Brown & Meulenbroek, 2016	Pre-professional; Age: 19.71±2.09; Males & Females	Classical ballet	Inertial sensors	Port de bras in bras-bas, 1st, 2nd, 3rd, 3rd reversed, 1st, bras-bas, demi seconde allongé & bras- bas	-	Low to moderate
52. Steinberg et al., 2016	Elite; Age: F - 16.67±1.79, M - 15.90±1.42; Males & Females	Classical ballet	Inertial sensors	Postural sway in coud-de-pied and fondu	Male vs. Female	Moderate to serious
53. Abraham et al., 2016	Elite; Age: 31±1.87; Years of training: 22.8±4.14; Males & Females	Contemporary dance	Motion capture	Elevé	-	Serious
54. Coker et al., 2015	Elite; Age: 26.04±5.29; Years of training: 19.63±6.47; Female	Classical ballet	Motion capture; Force plates	Demi-plié & sauté in CP1	VI and KI vs. Mental arithmetic task as control group	RCT High Risk
55. Jarvis & Kulig, 2015	Elite; Age: Between 18 and 35; Years of training: At least 10; Female	Classical ballet and modern dance	Motion capture; Force plates	Relevé, sauté & saut de chat in CP1	Elite vs. non-dancers	Moderate
56. Bronner & Shippen, 2015	Pre-professional & Elite; Age: Elite - 25.8±2.6, Pre-professional - 20.4±1.5; Years of training: Elite - 15.22±6.68, Pre-professional - 5.5±5.15; Males & Females	Classical ballet	Motion capture	Développé arabesque with and without elevé in CP1	Elite vs. pre-professio nal	Moderate to serious
57. Gontijo et al., 2015	Age: 27±8 ; Years of training: 18±8; H/w: 4±2 classes per week (no hours)	Classical ballet	Motion capture	Demi-plié & grand-plié in CP1	-	Moderate
58. Hackney et al., 2015	Age: 20.89±2.93; Years of training: at least 5; Female	Classical ballet	Motion capture	Échappé sauté from CP1 to CP2 to CP1	-	Low to moderate
59. Tanabe et al., 2015	Pre-professional; Age: 24.1±5; Years of training: 14.4±3.6; Female	Classical ballet	Video analysis; EMG: Gm, RF, SAR, VL, BF, SM, MGAS, LGAS, SOL, FIB, TA, EDL, FHB	CP1 to CP6 & elevé	-	Low to moderate
60. Tanabe et al., 2014	Pre-professional; Age: 22.78±4.68; Years of training: 11.56±4.8; Female	Classical ballet	Video analysis; Force plates	Elevé	Dancers vs. non-dancers	Low to moderate

Study	Participants	Category of dance	Sensing Technology	Ballet movement	Comparison between groups	Risk of bias
61. Lin et al., 2014	Elite & Novices; Age: Superior experience - 18.2±1; Experienced - 18.3±5.7, Novice - 12.3±1.6; Years of training: Superior experience - 9.8±1.7, Experienced - 8.6±4.9, Novice - 3.3±1.7; H/w: Novices - 1.5-3h, Advanced - at least 3h; Female	Classical ballet	Motion capture; Force plates	Retiré passé in CP5	Elite vs. Novice	Moderate
62. Fong Yan et al., 2014	Pre-professional; Age: 25±5.9; Female	Classical ballet	Motion capture; Force plates	Sauté in CP2	Barefoot vs. jazz shoes	Low to moderate
63. Lin et al., 2014	Pre-professional; Age: Injured - 19±2, Non-injured - 17.7±2.6; Years of training: at least 5; Female	Classical ballet	Motion capture; Force plates; EMG: FIB, MGAS, TA	Grand-plié in CP1	Injured vs. non-injured	Moderate to serious
64. Lin et al., 2013	Elite & Novices; Age: Novices - 12±1.91, Advanced - 17.77±3.39; Years of training: Novices - 3.23±1.69, Advance - 8.69±3.3; H/w: Novices - 1.5-3h, Advanced- at least 3h; Female	Classical ballet	Motion capture	En dehors pirouette in CP4	Elite vs. Novice	Moderate to serious
65. Torrents et al., 2013	Pre-professional; Age: F - 28±12.7, M - 31±9.9; Years of training: at least 5; Males & Females	Contemporary dance	Motion capture	Tour en dehors, brisé volé en arrière en tournant, arabesque penchée	-	Low to moderate
66. Kiefer et al., 2013	Elite; Age: 23.59±3.99; Males & Females	Classical ballet	Force plates	Demi-plié & elevé	Elite vs. non-dancers	Low to moderate
67. Wyon et al., 2013	Pre-professional; Age: 20±1.74; Female	Contemporary dance	Inertial sensors	Grand-jeté	-	RCT High Risk
68. Lobo da Costa et al., 2012	Pre-professional; Age: 18.4±2.8; Years of training: at least 7; Female	Classical ballet	Force plates	Attitude devant, derrière & a la second	Ballet shoes vs. barefoot	Low to moderate
69. Lee et al., 2012	Age: 19.73±2.41; Years of training: at least 7; Female	Classical ballet	Motion capture; Force plates; EMG: FIB, TA, MGAS (both legs), VM, VL, AD, BF (dominant leg)	Sissonne fermée in CP5	Injured vs. non-injured	Moderate
70. Pearson & Whitaker, 2012	Pre-professional; Age: 19.63±1.06; Years of training: At least 2 in pointe shoes; Female	Classical ballet	Force plates	Demi-pointe in CP1	Dancers with different shoes	Low to moderate
71. Shippen et al., 2012	Pre-professional; Age: 23; Female	Contemporary dance	Motion capture; Force plates	Contemporary sequence	-	Moderate

Study	Participants	Category of dance	Sensing Technology	Ballet movement	Comparison between groups	Risk of bias
72. Bronner, 2012	Elite & pre-professional & Novices ; Age: Elite - 24.9±1, Intermediate - 19.6±0.5, Novice – 19.8±0.5; Years of training: Elite - 13.3±1.9, Intermediate - 11.7±1.1, Novice – 6.1±1.6; Males & Females	Classical ballet	Motion capture	Développé arabesque in CP1	Elite vs. Pre-professional vs. Novices	Moderate
73. Krasnow et al., 2012	Elite & pre-professional & Novices; Age: 30.0±13; Years of training: 13.9±13.3; Female	Classical ballet and modern dance	Motion capture; Force plates	Grand battement in CP1	Elite vs. pre-professional vs. novices	Moderate to serious
74. Charbonnier et al., 2011	Pre-professional & Elite; Age: 25.36; Years of training: at least 10; H/w: at least 12; Female	Classical ballet and modern dance	Motion capture	Arabesque, développé devant, développé a la seconde, grand écart facial, grand écart lateral & grand plié	-	Low to moderate
75. Lin et al., 2011	Pre-professional; Age: Injured – 19.7±2.4, Non-injured - 18.8±3.1; Years of training: at least 7; Female	Classical ballet	Motion capture; Force plates	CP1 & CP5	Injured vs. non-injured vs. non-dancers	Low to moderate
76. Walter et al., 2011	Pre-professional; Age: 19.94±1.16; Years of training: 14.17±2.92; H/w: 22.97±8.41; Female	Classical ballet	Force plates	Assemblé in CP5	Flat shoes vs. Pointe shoes	Low to moderate
77. Hackney et al., 2011	Pre-professional; Age: 22.72±2.63; Female	Classical ballet	Motion capture	Grand-jeté	-	Low to moderate
78. Hackney et al., 2011	Pre-professional; Age: 21.31±2.06; Female	Classical ballet	Video analysis; Force plates	Grand-jeté	-	Low to moderate
79. Hackney et al., 2011	Pre-professional; Age: 22.72±2.63; Years of training: at least 5; Female	Classical ballet	Video analysis; Force plates	Sauté in CP1	-	Low to moderate
80. Bronner & Ojofeitimi, 2011	Pre-professional; Age: 20.76±2.46; Years of training: 10.74 ± 4.50; Males & Females	Contemporary dance	Motion capture	Grand battement devant, derrière & a la second in CP1	-	Low to moderate
81. Kulig et al., 2011	Pre-professional; Age: 18.9±1.2; Years of training: 8.9 + 5.1 ; Males & Females	Classical ballet	Motion capture; Force plates	Saut de chat	-	Serious

Study	Participants	Category of dance	Sensing Technology	Ballet movement	Comparison between groups	Risk of bias
82. Golomer et al., 2010	Elite; Age: Dancers - 19±1.6, Non-dancers – 19±1.3; Years of training: at least 10; H/w: 35; Female	Classical ballet	Seesaw platform; Force plates	Postural sway in one leg	Elite vs. non-dancers	Low to moderate
83. Imura et al., 2010	Pre-professional; Age: 27.7±1.7; Years of training: 20.6 ± 3.2; Female	Classical ballet	Motion capture; Force plates	Fouetté turns	-	Low to moderate
84. Golomer et al., 2009	Elite; Age: 19±2; Female	Classical ballet	Motion capture	Pirouette in CP4	-	Low to moderate
85. Golomer et al., 2008	Elite; Age: 19.6±1.3; Female	Classical ballet	Motion capture	Pirouette in CP4	Elite vs. non-dancers	Moderate
86. Imura et al., 2008	Pre-professional; Age: 27.7±1.7; Years of training: 20.6 ± 3.2; Female	Classical ballet	Motion capture; Force plates	Fouetté turns	-	Low to moderate
87. Chockley, 2008	Pre-professional; Female	Classical ballet	Force plates	Sauté in CP1	-	Moderate
88. Couillandre et al., 2008	Elite; Age: 31±9; Female	Classical ballet	EMG: VL, BF, TA, SOL; Inertial Sensors	Demi-plié & sauté in CP1	-	Moderate
89. Golomer, 2007	Pre-professional; Age: 19±1.5; Female	Classical ballet	Motion capture	Pirouette in CP4	Dancers vs. non-dancers	Low to moderate
90. Lepelley et al., 2006	Pre-professional & Elite; Males & Females	Classical ballet and modern dance	Motion capture; EMG: ES, GM, RA, P, BF, RF, VL, LGAS, SOL	Battement jeté	-	Low to moderate
91. Bronner & Ojofeitimi, 2006	Elite; Age: F - 30.7±6.4, M - 26.7±4.9; Years of training: F - 22.2±6.1, M - 14.2±3.7; Males & Females	Classical ballet and modern dance	Motion capture	Retiré passé in CP1	Male vs. Female	Moderate to serious
92. Lin et al., 2005	Pre-professional; Age: 19.15±1.9; Years of training: 11.37±3.9	Classical ballet	Motion capture; Force plates	Relevé in CP1	-	Low
93. Thullier & Moufti, 2004	Elite	Classical ballet	Motion capture	Rond de jambé	Elite vs. non-dancers	Low
94. Golomer & Dupui, 2000	Elite; Age: F - 23.3±6.7, M - 24.1±1.5, Untr. F – 19.7±2.6, Untr. M - 24.3±3; Males & Females	Classical ballet	Seesaw platform; Inertial sensors	Postural sway	Elite vs. non-dancers	Serious
95. Golomer et al., 1999	Elite; Age: Dancers - 23.8±2.2, Non-dancers - 18.8±3.5; Males	Classical ballet	Seesaw platform; Inertial sensors	Postural sway	Elite vs. non-dancers	Serious

Study	Participants	Category of dance	Sensing Technology	Ballet movement	Comparison between groups	Risk of bias
96. Golomer et al., 1999	Elite & Novices; Age: Adults - 23.8±2.2, Adolescents - 18.1±0.9, Novices - 11.6±1.3; Males	Classical ballet	Seesaw platform; Inertial sensors	Postural sway	Elite vs. Novice	Serious
97. Golomer et al., 1997	Elite & Novices; Age: Elite - 17.4±1.1, Novices - 11.9±1.1, Acrobats elite - 18.1± .1, Acrobats novices – 12.5±1.5; Female	Classical ballet and acrobats	Seesaw platform; Inertial sensors	Postural sway	Elite vs. vs. acrobats vs. Novice	Serious
98. Trepman et al., 1993	Elite; Age: 33±9; Years of training: 24±10; H/w: 32±7; Female	Classical ballet and modern dance	Video analysis; EMG: GM, BF, AD, VL, VM, TA, MGAS, LGAS	Demi-plié in CP1	ballet vs. modern	Low to moderate

4.3.5 Sensing Technology

Forty-four studies used two or more types of technology to collect data, showing that 26 studies combined kinematic with kinetic analysis, 4 studies combined kinematic and kinetic analysis with EMG, 2 studies combined kinematic and kinetic analysis with inertial sensors, 4 studies combined kinematic analysis with EMG, 2 studies combined kinetic analysis with EMG, 5 studies combined kinematic analysis with inertial sensors, and only 1 study combined EMG with inertial sensors. The other 36 studies used only one type of technology to collect data, showing that 23 studies performed kinematic analysis (all used motion capture technique), 10 studies performed kinetic analysis (all used force plates), and 3 studies used only inertial sensors (Table 1). Overall, 64 studies performed kinematic analysis (49 studies used motion capture as technique), whereas 45 studies performed kinetic analysis (42 studies used force plates as technique). Twelve studies used inertial sensors as a technique, and only 11 studies used EMG.

4.3.6 Classical Ballet Movements Evaluated

In this systematic review, an amount of 29 ballet movements were analyzed within the selected articles (Table 1). The ballet movement with the most frequency of analysis was the *sauté* (15 studies). The second most studied movements were the *grand-jeté* and *saut de chat* (12 studies)*.* Postural sway was analyzed in 9 studies, followed by the movement *demi-plié* and *en dehors pirouette* (both with 8 studies). Six studies analyzed the *grand-plié* movement. Static ballet feet positions and turnout of the hips were analyzed in 6 studies, and 7 other studies analyzed the *elevé* movement. Five studies analyzed the *arabesque* movement, and 4 studies analyzed the *relevé* movement. Three studies analyzed the *retiré passé* movement. Only 1 study analyzed upper limb ballet movements in a sequence of *port de bras*. Seventeen remaining movements were studied only once or twice, and the full list can be assessed in Table 1.

4.3.7 Relationship Between Evaluated Ballet Movements and Sensing Technologies

Only 4 studies analyzed kinematics, kinetics and EMG as protocol, and the selected movements were *grand-plié*, *relevé*, *sissonne fermée*, *arabesque*, and *cou-de-pied derrière* with *demi-plié* to *arabesque*.

Electromyography was analyzed in the following movements: *demi-plié* (3), *grand-plié* (1), *sauté* (2), 6 ballet positions (2), *elevé* (2), *relevé* (1), *arabesque* (2), *sissonne fermée* (1), and *battement jeté* (1).

Research that combined kinematic and kinetic analysis, have studied the following ballet movements; postural sway (5), *saut de chat* (5), *grand-jeté* (4), *en dehors pirouette* (3), *sauté* (3), *relevé* (2), *fouetté* turns (2), *entrelacé* (1), *ballonné* (1), *assemblé dessus* (1), *bourrés* (1), *demi-plié* (1), *retiré passé* (1), *elevé* (1), contemporary sequence (1), *grand battement* (1), feet position (1).

Regarding the studies that only used one type of technology, 23 studies used motion capture systems to analyze kinematic variables of ballet movements such as *demi-plié* (4), *grand-plié* (3), *sauté* and *échappé sauté* (3), turnout of hips (3), *elevé* (2), *grand-jeté* (1) *battement fondu* (1), *ballonné* (1), *sissonne fondu* (1), *arabesque* (4), *en dehors pirouette* (5), *brisé volé* (1), *développé* (3), *grand battement* (1), whole body rotation (2), *retiré passé* (1), and *rond de jambé* (1). Ten studies only used force plates to analyze kinetics of ballet movements such as *grand-jeté* (1), *sauté* (2), *grand-plié* (1), *retiré passé* (1), *elevé* (2), *attitude* (1), *assemblé* (1), and postural sway (3). Three studies only used inertial sensors to analyze ballet movements such as *grand-jeté* (1), upper limb ballet postures (1), postural sway (1), and *cou-de-pied* with *fondu* (1).

4.3.8 Relationship Between Motor Behavior and Brain Functional Analysis

Four studies were included regarding motor control approach with brain functional analysis. Those studies were performed by the same group of researchers, [82, 84, 85, 89]. The authors have studied visual imagery and spatial context in combination with a motor control approach in the *pirouette* ballet movement. Visual imagery was assessed by the Vividness of Movement Imagery Questionnaire (VMIQ), and the authors evolved their research throughout the years, studying then the right hemisphere in visual regulation of complex equilibrium, since their previous research showed the influences of visual cues in the postural sway of ballet dancers.

4.4 DISCUSSION

In order to increase the scientific knowledge associated with the performance of ballet movements, the aim of this systematic review was to describe the technology tools and devices used in data capture to analyze human performance and motor behavior of ballet movements. This review outlines the category of analyzed ballet movements in combination with sensing technology.

Classical ballet has a large lexicon of specific movements; consequently, this research field is still emerging. We found that only 29 ballet movements have been analyzed regarding the motor behavior approach, which means that a baseline of data is being created in order to evolve to more complex movements.

Regarding the category of dance, most of the selected studies are in the classical ballet field [20-22, 24, 25, 28, 30-33, 35-41, 44-49, 51, 52, 54, 56-64, 66, 68-70, 72, 75-79, 81-89, 92-97], although contemporary and modern dance became more popular recently [19, 23, 26, 27, 29, 34, 42, 43, 50, 53, 55, 65, 67, 71, 73, 74, 80, 90, 91, 98], probably because those categories of dance are offered in the curriculum of several colleges, since 22 out of 80 studies in this systematic review described participants as college dancers. Those participants were regarded as pre-professionals.

While disparities in skill levels were recognized between elite dancers and novices, mostly reporting that elite dancers have more effective and refined strategies regarding motor behavior and human performance (i.e. ground force reactions, limb symmetry, muscle co-activation and so on), it is important to reach consensus in what is considered an elite dancer, as the definition of this category of dancers showed to be arbitrary in the evaluated studies [20, 21, 31, 33, 36, 50, 56, 61, 64, 72-74, 82, 90, 96, 97]. Number of years of practice, hours of training per week and professional career in ballet may be accurate factors to consider a professional dancer as an elite dancer. In other words, it is reasonable to think that elite dancers display higher performance in ballet movements than novices, however, it is important to establish a definition of what may be assured as elite dancer. Nonetheless, most of the studies included in the present systematic review had pre-professional dancers as participants, which allowed the understanding of movement pattern, but do not represent the supremacy of the elite ballerina body. Study design in the published articles using pre-professional dancers should be redone with elite dancers as a follow up.

In effect, ballet research remains a field of interest in universities, mainly in graduate programs, and we found that only 28 out of 80 studies had some sort of funding or grants [20, 24, 25, 27–29, 31, 32, 38, 41–43, 46, 48–50, 55, 59, 63–65, 73, 80, 82, 83, 87, 89, 96].

Kinematic and kinetic analysis are the prevalent techniques, having motion capture systems and force plates as the prevalent measurement tools, respectively. Our results reveal a lack of consensus in the research protocol regarding the experimental design, since several studies arbitrarily selected the movements but did not follow up with different tools to compliment and improve data reliability. Combining two or more measurement tools may be paramount to optimize data collection and increase data reliability.

One limitation of the research studies so far is concerning the elements involved in motor coordination of ballet movements. For instance, only one study has analyzed upper limb movements of classical ballet [51]. In spite of accepting a higher relevance of the lower limbs in the performance of ballet movements, upper limbs may also have a significant contribution to increase balance and movement fluidity, as we have found that postural sway plays an important role in motor control of ballet movements [28, 41, 44, 52, 82, 94-97]. Therefore, this gap could be suggested as an issue for further research, regarding coordination and motor synergies formation during the learning process and performance of ballet movements. For instance, ballet movements directly involving the neck and head, such as specific techniques to perform several revolutions in *pirouettes* have not been studied yet. Variables such as movement speed, accuracy and precision can be measured through motor behavior tools, also in conjunction with upper limb and postural data collection.

Differences in sex regarding motor behavior is well studied in the literature, and assumptions of sex differences have also been made in ballet research. Only 4 out of 80 studies in this systematic review actually made comparisons between males and females [21, 48, 52, 91]. This is a topic for future research regarding motor behavior and human performance in ballet.

The involvement of neuroscience in dance research has evolved in the past decade. Numerous studies combined imagery techniques and technology such as magnetic resonance imaging and electroencephalography [8, 99-101] , as well as the mirror neuron system [102, 103], in order to comprehend the neurophysiology of ballet movements. However, just a few of those studies aimed to analyze brain-behavior connection, such as the studies included in this systematic review [82, 84, 85, 89]. It is of interest in ballet research to increase the knowledge regarding muscle-brain connection to better understand motor behavior and thresholds that distinguish levels of expertise. Perhaps it is the next obvious area of exploration.

The studies in this systematic review provide rich knowledge about kinematics and kinetics of ballet movements. It is evident that researchers know more about ballet nowadays than they knew in the past decades. Evidence has been built in ballet research regarding knowledge about motor behavior in dance, possibly allowing professional ballet companies and schools to better design ballet training in order to optimize human performance. Additionally, current findings in ballet research provide scientists with knowledge to pave the pathway for future and more complex data collection involving motor coordination, synergies and brain activation. However, questions regarding the threshold that distinguishes novices from elite dancers remain unanswered. Although this review did not aim to evaluate clinical applications of ballet movements, the findings suggest that several ballet movements may be elected as rehabilitation techniques for protocol design. Conclusions in the literature are often found as suggestions to elaborate and improve training in order to both enhance performance and prevent injuries, as well as to, in some cases, perform specific dance movements as protocols for physical rehabilitation of non-dancers.

4.5 CONCLUSION

This review highlighted the sensing technologies used to collect data of ballet movements. Findings reported an overview of the interests in motor behavior analysis regarding classical ballet movements. Studies in this review varied greatly considering study design and specific intervention characteristics. There is a broad collection of studies reporting motor behavior of several ballet movements with elite dancers, pre-professionals and novices, in classical ballet, modern and contemporary dance. Technology is constantly evolving, and researchers are allowed to use modern tools to answer old questions about the mystery between art and sport that is present in classical ballet. The future of ballet research is promising, and it is exciting to foresee the upcoming results regarding a motor behavior approach to evaluate classical ballet.

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CHAPTER 5:

Scientific Production - Article 2

Dissimilarities of the *demi-plié* movement trajectory in its different roles in classical ballet

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ABSTRACT

Demi-plié is a coordinated dance movement involving knees bent while keeping hips turned out and heels grounded. It consists of descending and ascending phases, the latter often preparing for the next move. Task goals may influence its trajectory. Ten classical dancers (eight females, two males), aged 20–45 years old performed *demi-plié* itself and prior to *pirouette en dehors, relevé, sauté*, and *sissonne fermée de côté*. Lower limb and hip trajectory data were collected through a motion capture system. Time-series data were aligned across all conditions using a dynamic time warping algorithm. The Euclidean distance measured the hip trajectory between each ballet movement, providing a continuous dissimilarity function over time. Descriptive analysis focused on each participant's maximum dissimilarity values across conditions. Results showed maximum hip trajectory differences of 40% for *demi-plié* before *sauté*, 30% before *sissonne*, 20% before *relevé*, and 10% before *pirouette*. Dissimilarities began in the descending phase of the *demi-plié*. ANOVAs for repeated measures and Bonferroni's post-hoc showed that the standard deviation of dissimilarity had the largest effect size for the *demi-plié* – *demi-plié* before *sauté*, and the smallest for the *demi-plié* – *demi-plié* before *pirouette*. *Demi-plié* prior to jumps demands plyometric forces and has open-loop motor planning, requiring acceleration, whereas *demi-plié* is closed-loop, relying on proprioceptive updating.

Keywords: *demi-plié*; dissimilarity; dynamic time warping; Euclidean distance; movement trajectory; ballet movement

5.1 INTRODUCTION

Demi-plié is a basic coordinated movement in classical ballet, which can be defined as a smooth, continuous bending of the knees until just below the hips, while maintaining turnout at the hip joints, allowing the thighs and knees to be directly above the toes line whereas the heels remain on the floor (Coker et al., 2015; Imura and Iino, 2017; Kim and Kim, 2016). The *demi-plié* acts as a sort of springboard for jumps, and it is critical for high performance turns, providing the impulse required for pivotal motion Imura and Iino, 2018).

The *demi-plié* is often used prior to performing other dance movements. Notwithstanding there is little scientific understanding of the *demi-plié* and its linkage to other dance movements at different levels of analysis, including kinematics, kinetics and muscular activity (Coker et al., 2015; Imura and Iino, 2017; Kim and Kim, 2016; Trepman et al., 1994; Wyon et al., 2013; Gontijo et al., 2015). By studying the *demi-plié* at any of these levels, we could better understand hypothetical differences in the coordination patterns involved in performing this basic ballet movement and its link to other subsequent movements.

To gain insight into the differences in the hip vertical trajectories of the *demi-plié* when linked to other ballet movements, the present study aimed to describe the dissimilarities of the *demi-plié* when it is performed in isolation and in preparation for four subsequent ballet movements such as: *demi-plié* for turning outward (*pirouette en dehors*); *demi-plié* for heel rises (*relevé*); *demi-plié* for vertical jumps (*sauté*); and *demi-plié* for lateral body displacement (*sissonne fermée de côté*). Hip vertical trajectories can be influenced by the descending and ascending phases of the *demi-plié* movement. For instance, the ascending phase of the *demi-plié* may change its speed depending on the subsequent movement, such as a heel rise or a vertical jump. Due to different task goals (e.g., performing a *demi-plié* to a *pirouette*) these phases can be performed differently, with different lengths as certain movements are faster and occur in less time than others. Coker and colleagues (2015) elucidated that the *demi-plié* and *sauté* constitute foundational movements in classical ballet but entail distinct sensorimotor planning requirements, as the *demi-plié* is a closed-loop movement reliant on proprioceptive updating, while the *sauté* involves a plyometric movement more characteristic of open-loop planning, which may have consequences at the coordination level. These differences can be captured by the hip vertical trajectory; therefore, we hypothesized that different movements associated with *demi-plié* would show differences in hip trajectories even when the time and rhythm of execution are the same.

To measure the dissimilarities between the various movements associated with *demi-plié*, the use of dynamic time warping (DTW) (Müller, 2007; Chalmers et al., 2011) and Euclidean distance (ED) (Herlina et al., 2018) seem to be suitable methods.

DTW is a method that matches two time series by stretching or compressing them along the time axis to minimize their distance. More precisely, this procedure stretches the two series onto a common set of time instants, repeating each element of the series as many times as necessary, such that the distance between them is the smallest. This technique can handle variations in timing and rhythm of execution, making it useful for comparing the same movement performed at different tempos or by different dancers. Based on empirical findings, it can be inferred that the performance of DTW is exceptionally high, irrespective of the size of the sample (Batista et al., 2014).

The ED measures the straight-line distance between two points in a multidimensional space and is commonly used in distance-based analyses (Herlina et al., 2018). ED is a simple and straightforward measure and it is relevant for many problems in several domains (Batista et al., 2014). For two time series of length n, $u = (u_1, \ldots, u_n)$ and $v = (v_1, \ldots, v_n)$, the ED is given by the square root of the sum of the squared differences between corresponding points:

$$ED(u, v) = \sqrt{\sum_{i=1}^{n} \left(u_i - v_i\right)^2}.$$

The novelty of the present study is the use of a running technique applied to ED. More precisely, we propose an innovative approach that includes using a moving window of fixed length and step one in which the ED is computed, providing a continuous dissimilarity function over time. This methodology was previously used with a different dissimilarity measure, in a study on hand trajectories of stroke patients before and after two rehabilitation programs (Passos et al., 2023). Consequently, it was expected that the outcomes of the present research would offer valuable insights into the distinct variations exhibited by the different phases of the *demi-plié* when performed in isolation or in preparation for various ballet movements. It is plausible that the descending and ascending phases of the *demi-plié* exhibit stronger alignment with the *sauté* rather than the *pirouette en dehors*, implying distinct utilization of the *demi-plié* in these ballet movements. The *sauté* aims to achieve maximum height, whereas the *pirouette en dehors* seeks to execute a balanced and smooth pivot in one leg.

In summary, the aim of the present study was to demonstrate that the apparently similar *demi-plié* when performed under different task goals, requires specific modes of coordination expressed by differences along vertical movement trajectories.

5.2 METHODS

5.2.2 Participants

Ten classical ballet dancers (8 females, 2 males), aged between 20 to 45 years old, with a minimum of six years of experience in classical ballet and currently active in the modality, participated in this study. The sample size was estimated using F-tests (ANOVA, Repeated Measures, Within Factors) for 1 group and 4 measurements, with a large effect size of 0.40, an alpha error probability of 0.05, a beta error probability of 0.20, and a correlation amongst measures of 0.50, which provided a total sample size of 10 subjects. This procedure was performed using the GPower software (version 3.1, Universität Düsseldorf, Germany). The determination to choose a substantial effect size as a parameter for sample size estimation was grounded in previous research concerning professional ballet dancers who performed the *sauté* movement in comparison to other vertical jumps, who also considered the plyometric movements derived from squat movement and knee flexion, which reported a similar magnitude of effect (Escobar Álvarez et al., 2020, 2022; Ávila-Carvalho et al., 2022).

Participants' demographics varied between pre-professional dancers, professionals currently working in professional dance companies, and amateurs practicing ballet classes as a hobby or for leisure (Table 1). All participants provided limb dominance information by answering which leg they would prefer to kick a ball and which hand they would prefer to throw and catch an object. Participants were healthy and had not suffered any injury within six months prior to the experiment date.

All participants provided signed informed consent for voluntary participation in the experiments. The research was approved by the local ethical committee, in accordance with the latest version of the Declaration of Helsinki for experimentation in humans.

Table1: Participants' demographics

Participants	Age	Height (m)	Years of Ballet Training	Hours of training per week	Dominant hand	Dominant leg	Characterization
1 Female	28	1.60	14	30	Right	Right	Professional
2 Female	34	1.63	20	30	Right	Right	Professional
3 Female	23	1.65	15	30	Right	Right	Professional
4 Female	21	1.64	14	10	Right	Right	Pre-professional
5 Female	20	1.59	12	8	Left	Left	Pre-professional
6 Female	20	1.60	12	8	Left	Right	Pre-professional
7 Male	21	1.69	9	7	Right	Right	Pre-professional
8 Male	21	1.71	6	5	Right	Right	Amateur
9 Female	45	1.70	35	4	Right	Right	Amateur
10 Female	22	1.65	6	6	Right	Right	Amateur

5.2.3 Data collection

The kinematic analysis room contained eight infra-red cameras (Optitrack Prime 13), using a sample rate at 100 Hz, arranged in the umbrella display formation, which captured the movements performed by the dancers in the center of the room. The room had linoleum flooring, commonly used in ballet classes and theater stages, and dimmed lighting to avoid interference or distraction.

Participants wore a non-reflective black suit, with reflective spherical markers of 3 cm of diameter located in strategic areas of the suit, in the lower limb, respecting the Calibration Anatomic System Technique (CAST) method for motion capture (Cappozzo et al., 1995). Reflective markers were displayed bilaterally in the posterior superior iliac spine (PSIS) and anterior superior iliac spine (ASIS), as well as rigid bodies composed by four reflective markers each, located bilaterally in the center of the outer thigh and leg of all participants.

Participants wore soft ballet shoes, regularly used in ballet training. A metronome was set at 64 bpm to encompass the rhythm and cadence of the *demi-plié* movement.

5.2.4 Experimental design

Participants performed the *demi-plié* and the *demi-plié* prior to four subsequent movements, as previously described. The order of ballet movements was randomly selected for each participant, all performed in the “first position” of classical ballet for both feet and arms, which is characterized as an external rotation of the thighs and legs, with both feet pointing outward, and arms elevated at the belly button height, with forearms slightly supinated and rounded with the hands facing the dancer. Participants had warmed up prior to measurements and testing.

The metronome configured at 64 bpm set the cadence of the descending phase of the *demi-plié*, clearly verbalized by the experimenter to perform the descending phase in two beats, to prepare for the ascending phase that would be fused to the subsequent movement, such as a heel rise (*relevé*) or a vertical jump (*sauté*).

Participants performed five repetitions of each experimental condition. The pilot trial showed that five repetitions of each experimental condition would be the optimum amount in order to avoid muscular fatigue, as the participants would have to perform five different experimental conditions in only one experimental session. The interval between experimental conditions was five minutes of rest for all participants. The total time of the experiment session was approximately 1 hour.

5.2.5 Data analysis

The data analysis approach involved isolating the descending and ascending phases of the *demi-plié* movement using an in-house developed MATLAB routine (version R2022b, MathWorks Inc., USA). This routine provided time series data that exclusively contained the *demi-plié* movement, enabling the selection of the appropriate phases for analysis. The data from the *demi-plié* movement itself were used as a model for selecting the corresponding phases for the other four movements.

The descending and ascending phases of the *demi-plié* movement were defined based on the Y-coordinate values relative to the hip vertical trajectory. Specifically, the descending phase was identified as the period when the Y-coordinate values began to decrease and ended when the coordinate stabilized. Conversely, the ascending phase was identified as the period when the Y-coordinate values began to increase and ended when the trajectory accelerated to engage in the subsequent movement.

The time series related to the hip vertical trajectory of each ballet movement were not of equal duration, as certain movements were faster and occurred in less time than others. This means that the ascending phase of the *demi-plié* changes its speed depending on the subsequent movement, such as a heel rise or a vertical jump. To align the time series data, another in-house developed MATLAB routine was used to implement the DTW algorithm, with the *demi-plié* movement serving as the basis for comparison with the other four movements. Next, the dissimilarities between the *demi-plié* trajectories in the different experimental conditions were measured, considering the innovative approach of using the running ED within a moving window of fixed length and step one, providing a continuous dissimilarity function over time by overlapping both movement trajectories for comparisons. It should be noted that, when considering a time series of length n, the number of sliding windows of length m can be calculated as $n-m+1$, for $m < n-1$. In our study, the length of the windows was specifically determined as one third of the movement cycle to capture the dissimilarity observed during the descending and ascending phase of the *demi-plié*. The running ED also used the *demi-plié* as the reference movement in comparison with the other four *demi-pliés* in preparation for the subsequent movements. The set of dissimilarity values was then stored for each participant and for each pair of movements, and descriptive statistics for dissimilarity, namely minimum and maximum, temporal index of minimum and maximum, as well as mean and standard deviation (SD) were computed and analyzed.

Shapiro-Wilk's and Mauchly´s tests were used to examine the normality and the sphericity, respectively, of the dissimilarity statistical metrics for the different movements. Subsequently, ANOVAs for Repeated Measures, with Bonferroni's post-hoc comparisons, were performed to evaluate the difference between the dissimilarity statistics' mean values of all four pairs of *demi-plié* movements. The probability $p < 0.05$ was set as the criterion for statistical significance. This part of the study was undertaken using the IBM SPSS software (version 28, IBM Inc., USA).

5.3 RESULTS

5.3.1 Dissimilarities along the movement trajectories

Concerning the outputs of the running ED applied to the pairs of *demi-plié* movements, exemplar data from participant P4 was randomly selected (Figure 1).

For the comparison between the *demi-plié* and the *demi-plié* prior to *pirouette en dehors*, the set of dissimilarity values displayed a maximum of 0.612 (in the window starting at point 2440) and a SD of 0.189. For the comparisons '*demi-plié* – *demi-plié* prior to *relevé*', '*demi-plié* – *demi-plié* prior to *sauté*', and '*demi-plié* – *demi-plié* prior to *sissonne fermée de côté'*, the dissimilarity exhibited maximums ED of 0.686, 0.950, and 0.712 (in the windows starting at points 2778, 703, and 2512) and SD values of 0.240, 0.303 and 0.257, respectively. Therefore, the pair '*demi-plié* – *demi-plié* prior to *sauté*' showed the largest maximum difference observed between movements, and also the largest SD.

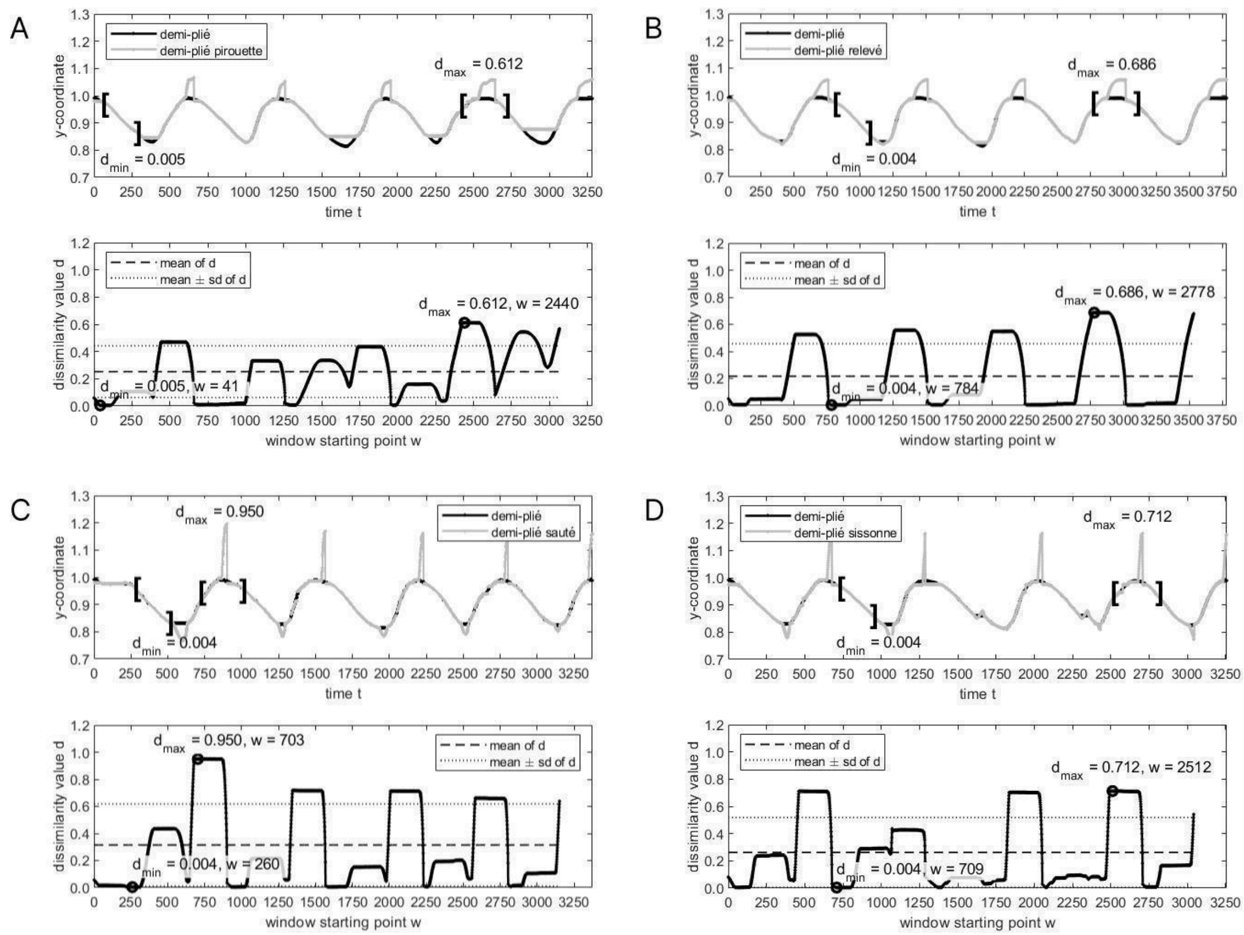

Figure 1: Outputs of the Euclidean distance (ED, d) for the four pairs of comparisons between the *demi-plié* and the *demi-plié* in preparation to subsequent movements, from participant P4, randomly selected, performing at a pre-professional level. A) *demi-plié – demi-plié* prior to *pirouette en dehors*; B) *demi-plié – demi-plié* prior to *relevé*; C) *demi-plié – demi-plié* prior to *sauté*; D) *demi-plié – demi-plié* prior to *sissonne fermée de côté*. d_{min} : minimum ED; d_{max} : maximum ED; SD: standard deviation ; w: window starting point (one third of the movement cycle). Brackets show the windows when the dissimilarity has occurred for both d_{min} and d_{max}.

The running ED within the moving window technique also made it possible to observe that the minimum dissimilarity occurred in the first and second cycles of the movement, precisely in the descending phase of the *demi-plié* for all pairs of movements, whereas the maximum dissimilarity occurred in the fourth and fifth cycles during the inversion phase, just before starting the ascending phase. However, for the pair *demi-plié* prior to *sauté*, the maximum dissimilarity occurred in the first two cycles of the movement.

5.3.2 Maximum dissimilarity values and variability analysis

In regard to the maximum and SD values of the dissimilarity for each participant, and each pair of movements, line plots are shown in Figure 2.

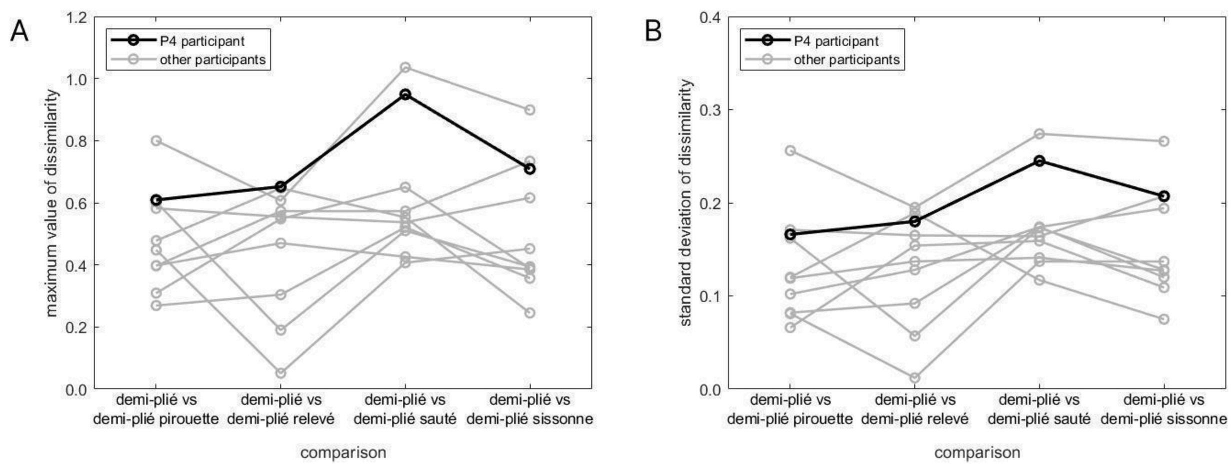

Figure 2: A) maximum values of dissimilarity for each participant and each pair of movements; B) standard deviation of dissimilarity for each participant and each pair of movements.

The results show that 40% of the participants exhibited the greatest dissimilarity between the *demi-plié* and the *demi-plié* prior to *sauté*. Another 30% of the participants exhibited the maximum differences between the *demi-plié* and the *demi-plié* prior to *sissonne fermée de côté*. Amongst the remaining participants, two participants (20%) exhibited the primary difference in the *demi-plié* prior to *relevé* and the remaining participant (10%) exhibited it in relation to the *demi-plié* prior to *pirouette en dehors.* Regarding the SD values, results show that 70% of the participants exhibited the highest values between the *demi-plié* and the *demi-plié* prior to *sauté*; 20% of the participants exhibited the highest values between the *demi-plié* and the *demi-plié* prior to *sissonne fermée de côté*; and 10% of the participants exhibited the highest values between the *demi-plié* and the *demi-plié* prior to *relevé.*

5.3.3 Statistical analysis

The ANOVAs for Repeated Measures, with Bonferroni's post-hoc, for the dissimilarity statistics across the four pairs of movements showed that: i) for the maximum ED value of dissimilarity, there was a result close to being statistically significant, with a large effect size ($F_{(3,27)}$ = 2.508, p = 0.080, η^2_p = 0.218), with the pair '*demi-plié – demi-plié* prior to *sauté*' displaying the largest maximum ED of dissimilarity and the pair '*demi-plié – demi-plié* prior to *relevé*' the smallest (0.616±0.2111 vs 0.460±0.208); ii) for the SD values of dissimilarity, there was a significant result, with a large effect size ($F_{(3,27)}$ = 3.381, p = 0.033, η^2_p = 0.273), in which the pair '*demi-plié – demi-plié* prior to *sauté*' exhibited the largest SD of dissimilarity and the pair '*demi-plié – demi-plié* prior to *pirouette en dehors*' the smallest (0.176±0.048 vs 0.133±0.057, p = 0.041). Regarding the other dissimilarity statistics, no significant results were obtained.

5.4 DISCUSSION

The present study found that the main differences between a *demi-plié* and a *demi-plié* prior to other movements were observed for the *sauté* and *sissonne fermée de côté*.

The running ED within moving window technique used a fixed window length of one third of the movement cycle, which could slide throughout the aligned time series and precisely show where the minimum and maximum dissimilarities occurred in the *demi-plié* when it was performed in preparation for subsequent ballet movements. This technique was an innovative approach in movement trajectory analysis, providing insight about the movement dynamics of the *demi-plié* movement.

We hypothesized that the same apparent *demi-plié* would show differences at coordination levels when it would present different end-goals. Indeed, through our innovative approach, our hypothesis has been confirmed, reporting that for most of the participants (70%), the largest SD was observed for the pair *demi-plié* – *demi-plié* prior to *sauté*, suggesting that the variability was not due to chance but was influenced by the type of movement being compared.

During a vertical jump, a net hip flexor torque is exerted, while the knee extensors and plantar flexor torques are exerted during the push-off phase, which was characterized as the ascending phase of the preparatory *demi-plié*. Through coordinated actions, gluteal synergies may occur to promote a plyometric movement, in combination with the contraction of the *rectus femoris* to act as a hip flexor, transferring power to the triceps surae to propel the body against gravity, suggesting a proximodistal control of lower limb action (Trepman et al., 1994; Gregoire et al., 1984).

Coker and colleagues (2015) explained that pelvic tilt movement is considered a measure of pelvic stability, with smaller values denoting more pelvic stability. The *demi-plié* has the tendency to achieve maximum hip-external rotation in the depth of the descending phase, whereas the maximum hip-external rotation for the *sauté* happens during the jumping and landing, instead of during the preparatory *demi-plié*. However, in the present study, we limited our analysis to the *demi-plié* in preparation for *sauté*, not analyzing the *sauté* movement itself, which suggests that anticipatory adjustments are made during the *demi-plié* in preparation for the vertical jump, as the dissimilarities regarding minimum and maximum distance between *demi-pliés* occurred already in the descending phase.

The *sissonne fermée de côté* is a jump-land ballet movement with lateral body displacement, starting with a *demi-plié* for impulse to a vertical jump and immediately displace the body laterally, as the ballet dancer simultaneously extends both legs in the air as scissors, having the leading leg raised at approximately 22.5 degrees away from the midline of the body, and the trailing leg rising by pushing off the ground (Lee et al., 2012). It makes sense that the *demi-plié* prior to *sissonne fermée de côté* showed the main significant differences alongside the *demi-plié* prior to *sauté*. The leading leg plays a crucial role in initiating the movement by plantarflexing the ankle and extending the knee. It also takes on the responsibility of absorbing impact force upon landing. On the other hand, the trailing leg has the task of stabilizing the body before the leading leg contacts the ground. Once the leading leg touches the ground, the trailing leg swiftly moves closer to it.

In regard to the findings of the *demi-plié* prior to *relevé*, this movement requires impulse for heel rise, which is basic for subsequent movements such as *pirouette* and walking in the ballet pattern of “toe to heels”. Performing a *relevé* is an action that also requires plyometric forces, maintaining constant plantar flexion with raised heels and extended legs. The proximodistal control of lower limb action may be applied to the *relevé* as well, as this movement is performed dynamically, reaching the depth of the descending phase of the *demi-plié* in order to activate plyometric forces for a fast and quick heel rise, precisely the phase where dissimilarities begin.

Our sample included various levels of expertise in classical ballet, however, with a small number of classical dancers for each level of expertise. This was a limitation in our study, and it would be interesting to reproduce the experiment with a larger group of various levels of expertise in order to make comparisons between groups. Our analysis solely involved the vertical hip trajectory as a dependent variable for finding dissimilarities between the *demi-plié* movement when it was performed in preparation for other ballet movements. However, it would be interesting to analyze other variables such as the knee angles in order to find the possible synergies that occur between limbs. Additionally, since we observed anticipatory adjustments already in the descending phase of the *demi-plié*, it would be interesting that future research investigates brain electrical activity in order to possibly find distinct activation patterns.

These findings bring knowledge to the fact that designing ballet training and rehearsals must take into consideration how the body can be overwhelmed by simply repeating movements that are apparently similar. Ballet dancers develop numerous injuries along the course of their careers, and injury prevention in dance has been a trendy topic in motor behavior research (Li et al., 2022; L Biernacki et al., 2021; Kaufmann et al., 2021; Fuller et al., 2020) as well as the interest in understanding how ballet movements are performed and the type of sensing technology used to collect data (Quadrado et al., 2022). Therefore, our findings contribute to this growing research field, focusing on understanding how the human body works in order to achieve the highly elite performance and aesthetic beauty as seen in classical ballet.

5.5 CONCLUSION

Dissimilarities of the *demi-plié* trajectory in its different roles in classical ballet were observed in preparation for both the *sauté* and *sissonne fermée de côté* ballet movements.

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CHAPTER 6:

Scientific Production - Article 3

Coordination patterns of the lower limb and pelvic complex during the *demi-plié* movement with different end-goals in classical ballet

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ABSTRACT

Demi-plié is a coordinated ballet movement involving a smooth, continuous bend of the knees, keeping hips turned out and heels grounded. Task goals may influence its coordination patterns. Twelve classical dancers (9 females, 3 males) performed the *demi-plié* itself and prior to other ballet movements such as: *pirouette en dehor*, *relevé*, *sauté*, and *sissonne fermée de côté*. Motion capture system was used for data acquisition of the lower limb and pelvic complex. Differences in coordination patterns in regards to the knees joint angles and angular velocities were found during the *demi-plié* performance in all five experimental conditions, showing similar results amongst all participants. Each *demi-plié* displayed different coordination patterns accordingly with the end goal. Notwithstanding, some of the experimental conditions presented a similar pattern. For all the participants, the *demi-plié* prior to *pirouette en dehors* showed a unique variability pattern, probably with the most amount of anticipatory adjustments due to the complexity of this motor action. Ballet dancers may learn multiple patterns of execution of the *demi-plié* when it comes to performing subsequent complex ballet movements.

Keywords: *demi-plié*; coordination pattern; intrapersonal coordination; ballet movement

6.1 INTRODUCTION

Demi-plié is a basic coordinated movement in classical ballet, performed similarly by both legs, which consists of two phases: descending phase and ascending phase. During the descending phase, the ballet dancer lowers the body by flexing their knees and ankle joints simultaneously, with external rotation of the hips, while maintaining heels on the floor and minimum pelvic tilt with an upright posture. The ascending phase of the *demi-plié* is initiated by the upward movement of the hip, which extends the thighs, knees and ankle joints simultaneously. The muscles of the lower limb work to accelerate the upward movement and control the ascent, as the ascending phase is often in preparation for subsequent muscles [1-3]. It acts as a sort of springboard for jumps being critical for high performance turns providing the impulse required for pivotal motion [4].

Regardless of the end-goal of the *demi-plié*, for instance, when it is in preparation for a vertical jump or for a heel rise, its execution looks similar to the observer. However, as the central nervous system (CNS) might use internal models as representations of motor action sequences [5], we assume that the CNS learns how the *demi-plié* must be performed, and it is possibly flexible in slightly adjusting kinematic variables of the *demi-plié* when it is in preparation for other subsequent ballet movements, thus, expressing different coordination patterns. Therefore, due to anticipation to the next movement, we hypothesize that intrapersonal lower limbs coordination patterns of this movement may present differences depending on its end-goal.

In human movement, coordination is the process of mastering redundant degrees of freedom of the moving structure [6]. It happens when two or more task elements interact in a way that stabilizes a specific performance goal. The notion of motor redundancy relates to having multiple solutions for accomplishing the same task, allowing a movement system to adapt fluidly to a constantly changing environment. This feature provides the system with the flexibility needed for adaptive motion, while also maintaining sufficient stability for reliable outputs, a crucial factor in motor performance [7]. Therefore, the CNS does not deal with just one way to solve a problem; rather, it enables a range of equally effective solutions for the same output.

In the present study, we considered the knees angles as task relevant elements, which hypothetically display variability and adaptability during the execution of the *demi-plié* when it is in preparation for different subsequent ballet movements. Complementarily, the pelvic complex potentially behaves as a performance variable to be stabilized by the task relevant elements, allowing the ballet dancer to maintain an upright posture and execute ballet movements that are initiated by a *demi-plié*. Our aim was to analyze the *demi-plié* movement in its different roles in classical ballet, in order to observe whether or not its execution presents different coordination patterns of the knees joint angles depending on its end-goal.

6.2 METHODS

6.2.1 Participants

Nine females and three males classical ballet dancers, aged between 20 to 45 years old, with a minimum of six years of experience in classical ballet and currently active in the modality, participated in this study. The sample size was determined using F-tests (ANOVA, Repeated Measures, Within Factors) for 1 group and 5 measurements, a medium effect size of 0.25, an alpha error probability of 0.05, a beta error probability of 0.20, and a correlation amongst repeated measures of 0.75, which provided a total sample size of 12 subjects. This procedure was performed using the GPower software (version 3.1.9.7, Universität Düsseldorf, Germany).

The demographic profile of the participants ranged from university students classified as pre-professional dancers, to professionals employed by dance companies, and hobbyists taking ballet for recreation (Table 1). Everyone indicated their dominant limb by specifying which leg they would use to kick a ball and which hand they would prefer for throwing and catching an item. Participants were healthy and had not suffered any injury within six months prior to the experiment date.

All participants provided signed informed consent for voluntary participation in the experiments. The research was approved by the Ethical Committee of the Faculty of Human Kinetics, University of Lisbon, (protocol number 32/2020) in accordance with the latest version of the Declaration of Helsinki for experiments in humans.

Table1: Participants' demographics

Participants	Age	Height (m)	Years of ballet training	Hours of training per week	Dominant hand	Dominant leg	Characterization
1 Female	28	1.60	14	30	Right	Right	Professional
2 Female	34	1.63	20	30	Right	Right	Professional
3 Female	23	1.65	15	30	Right	Right	Professional
4 Female	21	1.64	14	10	Right	Right	Pre-professional
5 Female	20	1.59	12	8	Left	Left	Pre-professional
6 Female	20	1.60	12	8	Left	Right	Pre-professional
7 Male	21	1.69	9	7	Right	Right	Pre-professional
8 Male	25	1.75	12	10	Right	Right	Pre-professional
9 Male	21	1.71	6	5	Right	Right	Amateur
10 Female	30	1.55	10	6	Right	Right	Amateur
11 Female	45	1.70	35	4	Right	Right	Amateur
12 Female	22	1.65	6	6	Right	Right	Amateur

6.2.2 Data Collection

The kinematic analysis room contained eight infra-red cameras (Optitrack Prime 13), with sample rate at 100 Hz, and displayed in the umbrella formation. The room had linoleum flooring, commonly used in ballet classes and theater stages, and dimmed lighting to avoid interference or distraction.

Participants wore a non-reflective black suit, with four reflective spherical markers of 3 cm of diameter located bilaterally in the hip to characterize the position of the posterior superior iliac spine and anterior superior iliac spine, as well as four sets of three reflective markers, located bilaterally in the outer thighs and shanks to characterize the knees joint angles based on lower limbs segments relative angles, respecting the Calibration Anatomic System Technique (CAST) method for motion capture [8]. Participants wore soft ballet shoes, regularly used in ballet training. A metronome was set at 64 bpm to encompass the rhythm and cadence of the *demi-plié* movement.

6.2.3 Experimental Design

Participants performed the *demi-plié* and the *demi-plié* prior to four subsequent movements, such as: *pirouette en dehors*, *relevé*, *sauté*, and *sissonne fermée de côté*. Participants were allowed to choose their preferred side to perform the *pirouette* revolution, as well as the lateral body displacement in the *sissonne*. The order of ballet movements was randomly selected for each participant, all performed in the "first position" of classical ballet for both feet and arms, which is characterized as an external rotation of the thighs and legs, with both feet pointing outward, and arms elevated at the belly button height, with forearms slightly supinated and rounded with the hands facing the dancer. Participants had warmed up prior to measurements and testing.

The metronome configured at 64 bpm set the cadence of the descending phase of the *demi-plié*, clearly verbalized by the experimenter to perform the descending phase in two beats, to prepare for the ascending phase that would be fused to the subsequent ballet movement.

Participants performed five repetitions of each experimental condition, with 5 minutes of interval between experiments. The pilot trial showed that five repetitions would be the optimum amount in order to avoid muscular fatigue, as the participants would have to perform five different experimental conditions in only one experimental session.

6.2.4 Data Analysis

In order to characterize the coordination patterns of the five experimental conditions, we first needed to isolate the *demi-plié* movement (i.e., the descending and ascending phases only) and then characterize how knees joint angles relate with the hip vertical movement in order to find possible distinctions in coordination patterns. Finally, we performed a statistical analysis to identify significant differences between left (L) and right (R) knees, as well as across the five experimental conditions.

6.2.4.1 Isolating the demi-plié from the subsequent ballet movements

The data analysis initial procedure involved isolating the *demi-plié* movement (i.e., the descending and ascending phases) using an in-house developed MATLAB routine (version R2022b, MathWorks Inc., USA). This routine provided time series data that exclusively contained the *demi-plié* movement of the five experimental conditions.

The descending and ascending phases of the *demi-plié* were characterized based on the Y-coordinate values relative to the hip vertical trajectory, based on the reflective markers for the posterior superior iliac spine and anterior superior iliac spine. Specifically, the descending phase was identified as the period when the Y-coordinate values began to decrease and ended when the coordinate stabilized. Conversely, the ascending phase was identified as the period when the Y-coordinate values began to increase and ended when the trajectory accelerated to engage in the subsequent movement.

6.2.4.2 Illustrating the demi-plié coordination patterns

In order to illustrate the spatial representation and characterize different coordination patterns, contour plots were designed considering the knees joint angles as elemental variables (X and Y-axis in Figure 2 corresponding to the right knee joint angle and the left knee joint angle, respectively) and the vertical hip trajectory as a performance variable (represented by the color gradient in Figure 2). Contour plots captured how the knees joint angles related with the hip vertical trajectory during the performance of the *demi-plié*. The color gradations highlight areas where the vertical hip trajectory varied according to the knees joint angles, helping in identifying patterns in the performance of the *demi-plié* in its different roles. The warmest colors (close to yellow) represent the highest height of the hip vertical trajectory, whereas the coolest colors (close to blue) represent the lowest height of the hip vertical trajectory. The contour plots were created through another in-house MATLAB routine using the data of the knees joint angles during the performance of the *demi-plié* of all experimental conditions.

6.2.4.3 Capturing the knees joint angles variability patterns

Due to slight adjustments that both knees are expected to perform to keep the hip vertical trajectory relatively stable, the variability of knees joint angles is investigated for different patterns. Since we hypothesized that the *demi-plié* would present different coordination patterns depending on its end-goal, we expected to find differences in the variability of the knees joint angles. These variability patterns were displayed by plotting the knees joint angles with the corresponding angular velocities in the descending and ascending phases of the *demi-plié* across the five experimental conditions.

To analyze that, another in-house MATLAB routine was created to measure the knees joint angles and the corresponding angular velocities during the execution of the *demi-plié* across all repetitions of all five experimental conditions. To potentially distinguish variability patterns of the *demi-plié* with different end-goals, phase portraits were plotted to compare left (L) and right (R) knees in all conditions for each participant.

6.2.4.4 Statistical analysis

Finally, statistical analyses were undertaken in order to identify significant differences between L and R knees, as well as across the five experimental conditions. L and R knees joint angles and angular velocities were calculated for each participant and each condition, and for inferential purposes, each time series of values was reduced to a mean and a standard deviation (SD). Shapiro-Wilk's tests were then used to validate the normality of each variable. Next, t tests for paired samples (and linear correlations) were performed for the L and R joint angles and angular velocities, for both the means and the SDs, of each experimental condition. Moreover, ANOVAs for repeated measures, with Bonferroni's post-hoc comparisons, were performed for the L and R joint angles and angular velocities, in terms of means and SDs, across the five experimental conditions. The probability $p < 0.05$ was set as the criterion for statistical significance. This part of the study was realized using the IBM SPSS software (version 28, IBM Inc., USA).

6.3 RESULTS

6.3.1 Coordination patterns

By the visual inspection of the contour plots it is possible to observe distinct coordination patterns in the contour plots for each *demi-plié* condition (Figure 2), especially in the performance of *demi-plié* prior to *pirouette en dehors* (Figure 2E). The spreading of the color stain in the contour plots seems visually different during the *demi-plié* performance for the five experimental conditions. However, for the *demi-plié* prior to *pirouette en dehors* (Figure 2E), the spreading of the color stain in the contour plot displays a completely different and unique coordination pattern. However, some of the experimental conditions appear to vary less than others. For instance, the performance of the *demi-plié* prior to *relevé* seems to be more similar to the simple *demi-plié*, than the performance of the *demi-plié* prior to *sauté* regarding the simple *demi-plié*. On the other hand, both the *demi-plié prior to sauté* and prior to *sissone fermée de côté* display similar coordination patterns.

Even though both knees movements are apparently symmetrical, by relating the lowest values of the hip vertical trajectory (dark blue color) with the knees joint angles of both axis in the contour plots, it is possible to notice interlimb differences. For instance, for both L (*y* axis) and R (*x* axis) knees joint angles in the performance of the simple *demi-plié* the L knee joint angle close up to 110 degrees whereas the R knee joint angle goes until 100 degrees (Figure 2A). In the *demi-plié* prior to *relevé* the left knee joint angle remains above 120 degrees whereas the knee joint angle goes slightly below 120 degrees (Figure 2B).

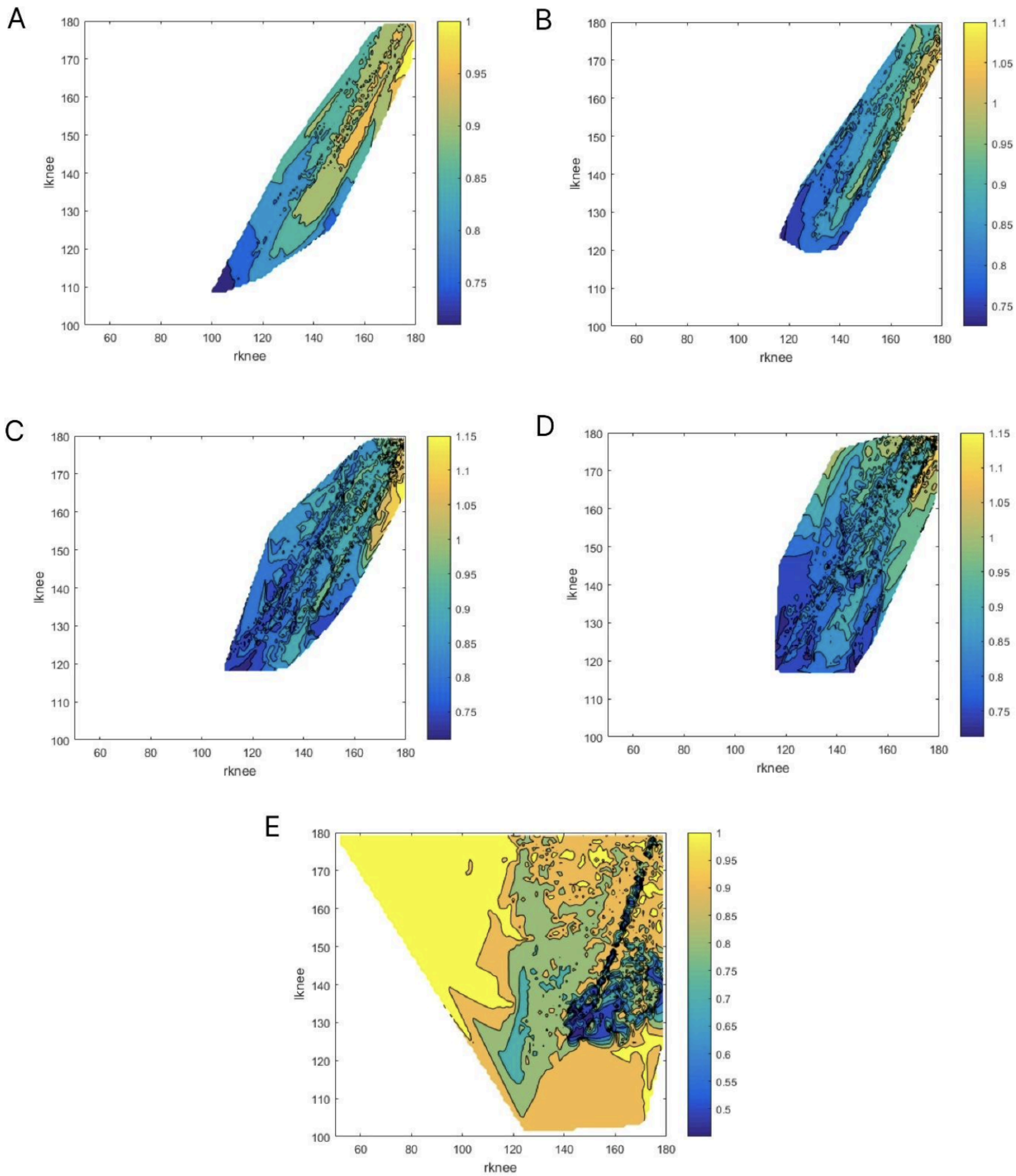


Figure 1: Coordination patterns of left and right knees joint angles during the *demi-plié* performance prior to subsequent ballet movements. A) simple *demi-plié*; B) *demi-plié* prior to *relevé*; C) *demi-plié* prior to *sauté*; D) *demi-plié* prior to *sissone fermée de côté*, and; E) *demi-plié* prior to *pirouette en dehors*. lknee: left knee; rknee: right knee. The color gradient identifies the height of the hip vertical trajectory. The warmest colors (close to yellow) identify the highest height, whereas the coolest colors (close to dark blue) identify the lowest height to the floor.

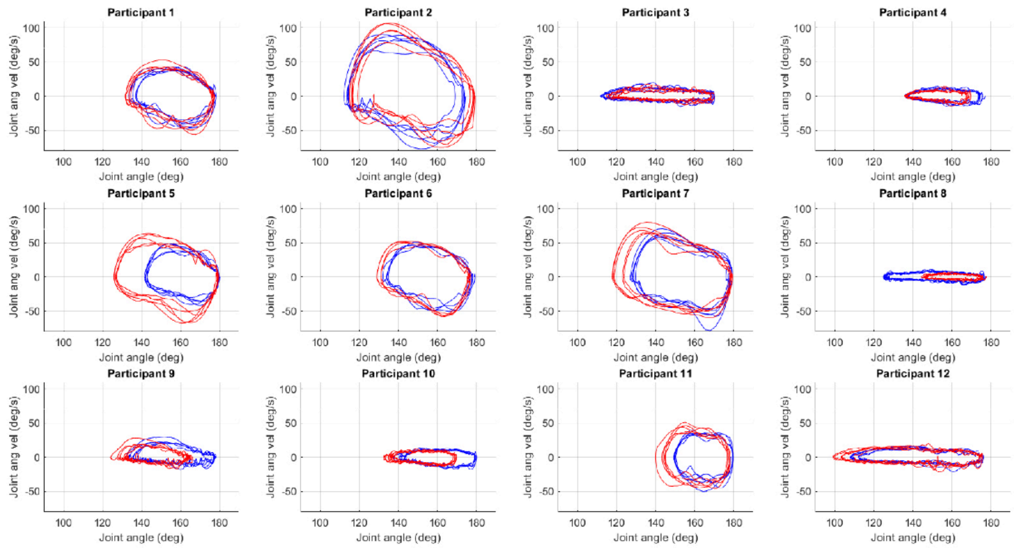
6.3.2 Knees joint angles and angular velocities

Phase portrait graphs were plotted in order to analyze the dynamics of L and R knees joint angles (Figure 3). Hence, it is possible to make comparisons between both knees by observing how similarly or differently they move. The shape and spread of the trajectory can indicate the stability of the knees movement during the *demi-plié* performance. For each plot, the overlapping of line trajectories is a sign of movement stability, while the separation of the trajectories characterize the existence of movement variability. Moreover, amongst participants two distinct variability patterns can be observed in the phase portraits: i) when the lines overlap in a flatten shape along the X-axis direction, and; ii) when the lines overlap in a circular shape in the graph.

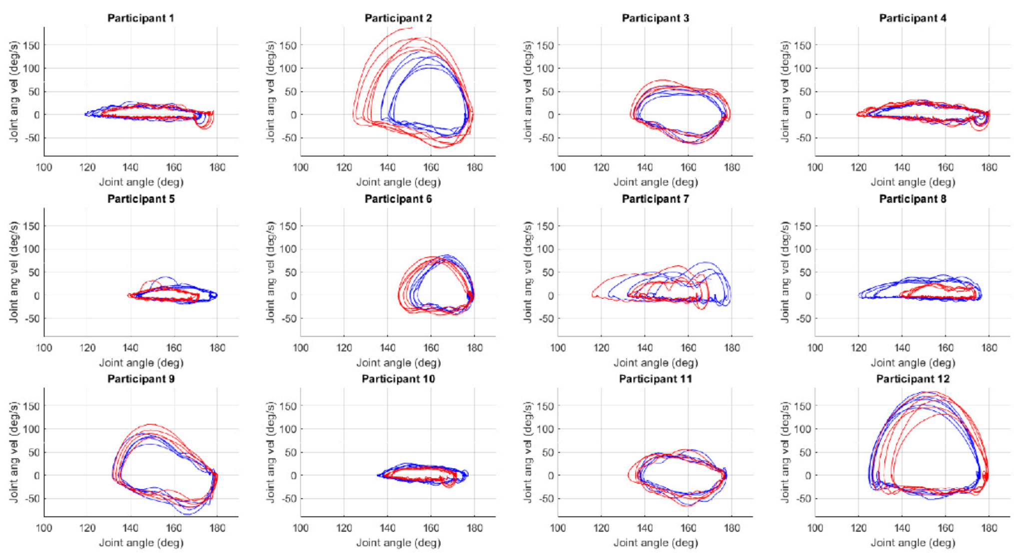
A visual inspection of the phase portraits display differences on interlimb stability for the five experimental conditions.

By the overlapping of the line trajectories the simple *demi-plié* (Figure 3A) and the *demi-plié* prior to *relevé* (Figure 3B) seem to be the movements with the most stability of both knees regarding the five experimental conditions. It is possible to observe consistency for all participants across the five repetitions performed in each condition. The *demi-plié* prior to *sauté* (Figure 3C) and the *demi-plié* prior to *sissone fermée de côté* (Figure 3D), both jump movements of classical ballet, due to a separation of the line trajectories, showed an increase in variability patterns of knees movement. Consequently, they displayed a less consistent shape of the phase portrait when compared with both simple *demi-plié* and the *demi-plié* prior to *relevé* (Figures 3A and 3B). On the other hand, the *demi-plié* prior to *pirouette en dehors* (Figure 3E) shows a distinct variability pattern when compared to the other four experimental conditions, showing less consistency in the shape of the phase portrait of the knees joint angles, probably displaying the least amount of *demi-plié* stability.

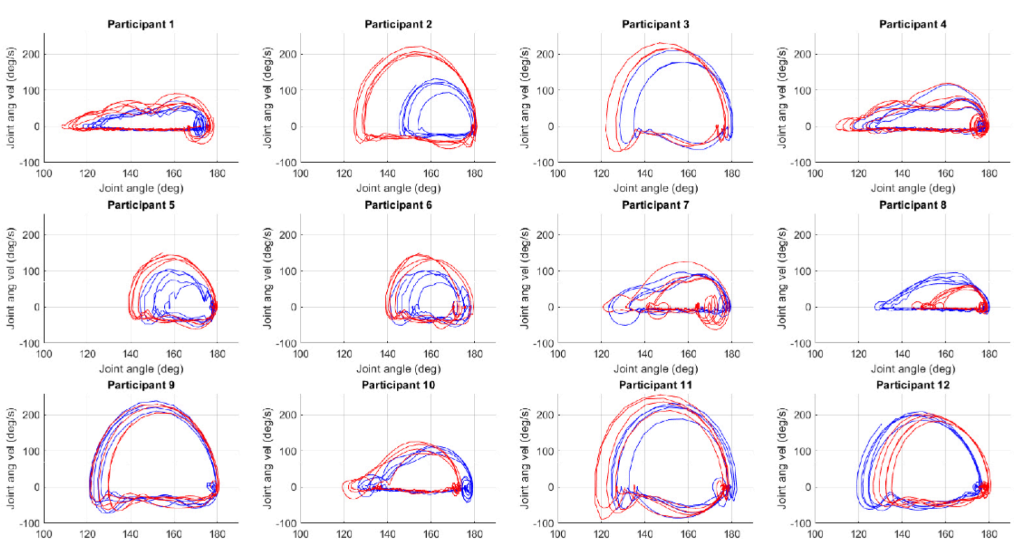
A


Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8
Participant 9
Participant 10
Participant 11
Participant 12
Joint ang vel (deg/s)
Joint angle (deg)

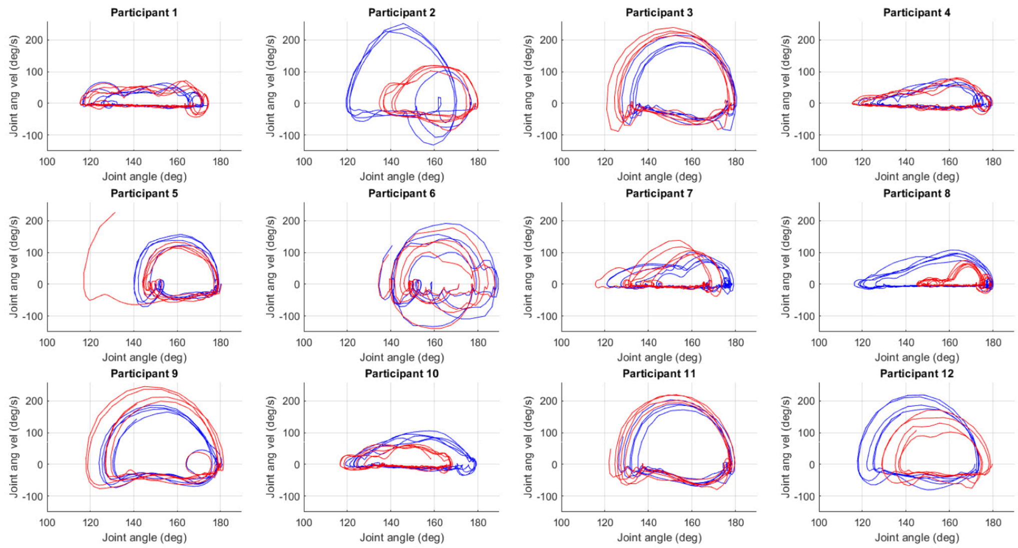
B


Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8
Participant 9
Participant 10
Participant 11
Participant 12
Joint ang vel (deg/s)
Joint angle (deg)

C


Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8
Participant 9
Participant 10
Participant 11
Participant 12
Joint ang vel (deg/s)
Joint angle (deg)

D



E

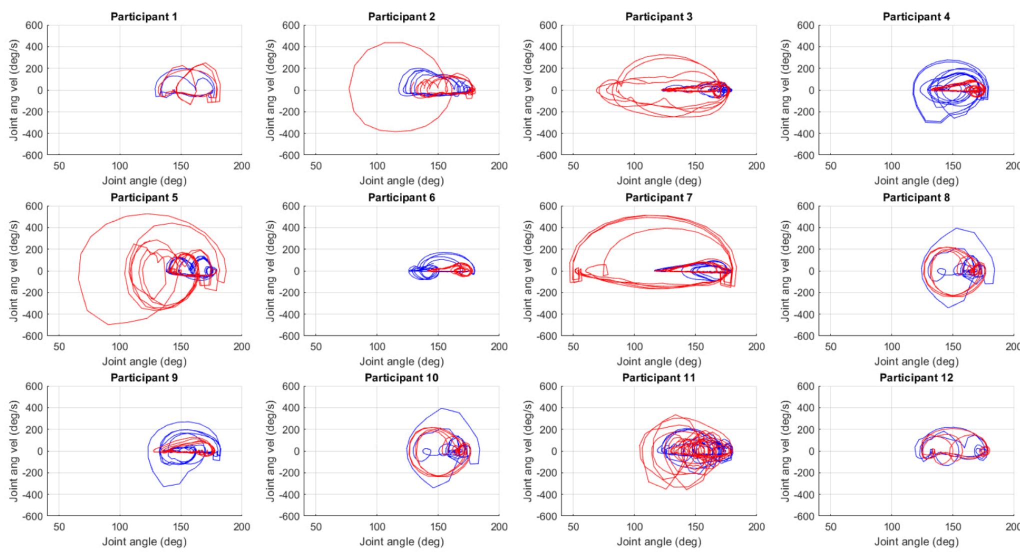


Figure 2: Phase portraits of the knees joint angles during the performance of the *demi-plié* for each participant in all five experimental conditions. The red line represents the right knee and the blue line represents the left knee. The X-axis represents the joint angle of knee flexion (in degrees) during the *demi-plié* performance, and the Y-axis represents the angular velocity of the knee joint (in degrees/second). A) simple *demi-plié*; B) *demi-plié* prior to *relevé*; C) *demi-plié* prior to *sauté*, and; D) *demi-plié* prior to *sissone fermée de côté*; E) *demi-plié* prior to *pirouette en dehors*.

6.3.3 Statistical analysis

Table 2 shows outputs of the statistical analysis regarding the t tests for paired samples (and linear correlations) for the comparisons between L and R knees joint angles and angular velocities. Significant results were found for the correlations between the means of L and R knees joint angles in all *demi-pliés*, except for the one in preparation for the *pirouette en dehors*, and for the correlations between means of both knees joint angular velocities in all conditions. Furthermore, significant correlations were obtained between the SD of L and R knees joint angles for the *demi-plié* and the *demi-plié* prior to *pirouette en dehors* and between the SD of the knees angular velocities in all conditions, excluding the *pirouette en dehors*. No significant differences were observed for the means between L and R knees variables.

Table 2: Correlations and comparisons of means and standard deviations (SD) of Left (L) versus Right (R) knees joint angles in degrees and angular velocities in degrees/second during the performance of the *demi-plié* and the *demi-plié* prior to four ballet movements. The asterisks represent significant results at 0.05 level.

Movement	Mean of L vs R Joint angle (deg)	SD of L vs R Joint angle (deg)	Mean of L vs R Joint angular velocity (deg/s)	SD of L vs R Joint angular velocity (deg/s)
1. *Demi-plié*	r = 0.737, p = 0.006* t = 0.841, p = 0.418	r = 0.759, p = 0.004* t = 0.145, p = 0.887	r = 0.969, p < 0.001* t = 0.827, p = 0.426	r = 0.984, p < 0.001* t = -1.485, p = 0.166
2. *Pirouette en dehors*	r = 0.158, p = 0.623 t = 0.977, p = 0.350	r = 0.759, p = 0.004* t = -0.751, p = 0.468	r = 0.758, p = 0.004* t = 1.913, p = 0.082	r = 0.330, p = 0.294 t = -1.776, p = 0.103
3. *Relevé*	r = 0.682, p = 0.014* t = 0.073, p = 0.943	r = 0.570, p = 0.053 t = 0.552, p = 0.592	r = 0.985, p < 0.001* t = 0.170, p = 0.868	r = 0.971, p < 0.001* t = -0.787, p = 0.448
4. *Sauté*	r = 0.787, p = 0.002* t = 1.060, p = 0.312	r = 0.565, p = 0.056 t = -0.162, p = 0.875	r = 0.957, p < 0.001* t = 0.046, p = 0.964	r = 0.914, p < 0.001* t = -1.931, p = 0.080
5. *Sissonne fermée de côté*	r = 0.709, p = 0.010* t = -0.076, p = 0.941	r = 0.052, p = 0.873 t = 1.195, p = 0.257	r = 0.901, p < 0.001* t = 0.309, p = 0.763	r = 0.934, p < 0.001* t = 0.885, p = 0.395

Table 3 presents outputs of the statistical analysis of means and SD for each knees joint angle and angular velocity across the five experimental conditions (ANOVAs for repeated measures), in which significant differences were only found in the angular velocities of both knees. Bonferroni's tests for multiple comparisons showed significant differences for the means comparisons of the L knee between the *demi-plié* and the *demi-plié* prior to *sissone fermée de côté*, and between the *demi-plié* prior to *relevé* and prior to *sissone fermée de côté*. In regards to the R knee, significant differences were obtained between the *demi-plié* prior to *pirouette en dehors* and the *demi-plié* prior to *sissone fermée de côté*. Moreover, the SDs showed significant differences for both knees between the *demi-plié* and the *demi-plié* prior to *pirouette en dehors,* and between the *demi-plié* prior to *relevé* and prior to *sissone fermée de côté*; the L knee showed differences between the *demi-plié* and the *demi-plié* prior to *sissone fermée de côté,* and the R knee showed between the *demi-plié* prior to *relevé* and prior to *sauté*.

Table 3: Analysis of means and standard deviations of each knees joint angle in degrees and angular velocity in degrees/second across the five experimental conditions with ANOVAs (main test) and Bonferroni's tests (multiple comparisons). L: left knee; R: right knee. The subscripts represent 1 – *demi-plié*, 2 – *demi-plié* prior to *pirouette en* dehors, 3 – *demi-plié* prior to *relevé*, 4 – *demi-plié* prior to *sauté*; 5 – *demi-plié* prior to *sissone fermée de côté*. The asterisks represent significant results at 0.05 level.

Variable	Main test (mean)	Multiple comparisons (mean)	Main test (standard deviation)	Multiple comparisons (standard deviation)
L joint angle (deg)	f = 2.280, p = 0.076 (η^2_p = 0.172)	---	f = 0.473, p = 0.635 (η^2_p = 0.041)	---
R joint angle (deg)	f = 2.046, p = 0.104 (η^2_p = 0.157)	---	f = 0.218, p = 0.767 (η^2_p = 0.019)	---
L joint angular velocity (deg/s)	f = 5.459, p = 0.011* (η^2_p = 0.332)	$P_{1,5}$ = 0.035* $P_{3,5}$ = 0.035*	f = 6.631, p < 0.001* (η^2_p = 0.376)	$P_{1,2}$ = 0.029* $P_{1,5}$ = 0.044* $P_{3,5}$ = 0.003*
R joint angular velocity (deg/s)	f = 6.948, p = 0.003* (η^2_p = 0.387)	$P_{1,2}$ = 0.049* $P_{1,5}$ = 0.043*	f = 7.782, p = 0.006* (η^2_p = 0.414)	$P_{1,2}$ = 0.009* $P_{3,4}$ = 0.039* $P_{3,5}$ = 0.044*

6.4 DISCUSSION

The aim of the present study was to analyze the *demi-plié* movement of classical ballet in its different roles, hypothesizing that it would reveal differences at the coordination level depending on the end-goal. Indeed, despite the visual similarity in the performance of a *demi-plié*, after isolating the descending and ascending phases from all experimental conditions, the contour plots displayed distinct patterns of coordination for all five experimental conditions, showing that the *demi-plié* performance is different depending on the end-goal. However, the main discrepancy noted in the contour plots, was in the performance of *demi-plié* prior to *pirouette en dehors,* possibly due to the fact that the *demi-plié* in preparation for a *pirouette en dehors* is often initiated with the feet in the "fourth position" of classical ballet, which is characterized by one leg in front of the other, both with legs in external rotation (turnout), and with some distance of approximately 10 cm between feet.

Concerning the phase portraits analysis, two different variability patterns were displayed in each experimental condition, showing different shapes amongst the participants, suggesting that the variability in the knee joint angles happened, but within an acceptable range of magnitude that did not compromise the stability of the performance variable (i.e., the pelvic complex). For instance, in the performance of the simple *demi-plié*, we observed that one of the phase portraits illustrates the tendency for a flat shape, as both lines are more horizontal across the X-axis. This variability pattern can be interpreted as if the velocity of the *demi-plié* performance was slower than the rhythm paced by the metronome. On the other hand, when we observe the other shape displayed in the simple *demi-plié* phase portrait, that illustrates a circle, we can interpret that the velocity of the *demi-plié* execution was close to the rhythm set by the metronome.

Participants from different levels of expertise performed all movements with excellence, displaying an acceptable range of functionality, perhaps due to anticipatory adjustments. However, the variability patterns displayed in the phase portraits showed that some of the experimental conditions presented a similar pattern. In other words, it seems that movements that do not have physical impact in its execution, as it is the case of the simple *demi-plié* and the *relevé*, the *demi-plié* performance is apparently similar, whereas when the ballet movement has some physical impact, as in the case of *sauté* and *sissone fermée de côté*, both jumps, the variability pattern showed similarities between them. As in the case to perform jumps, the participants needed to accelerate the ascending phase in order to get the proper impulse to take off the ground, which can have implications in the lower limb coordination, possibly explaining the similarities in the coordination patterns of *demi-plié* performance prior to both jumps. For all the participants, the *demi-plié* prior to *pirouette en dehors* showed a unique variability pattern, probably with the most amount of anticipatory adjustments due to the complexity to perform a revolution in only one leg, behaving as a pivot.

According to Robalo and colleagues [7], in a kinetic chain of movement, two proximal joints might reciprocally compensate to stabilize an end-effector (i.e., the most distal segment in the limb that interacts with the environment). End-effector variables are ‘controlled’, and directly linked to performance, whereas the task relevant elements are allowed by the system to have high variability, providing adaptability. In our study, we assumed the knees angles as task relevant elements, and the pelvic complex potentially as the performance variable, as it allows the ballet dancer to maintain an upright posture and execute ballet movements that are initiated by a *demi-plié*.

Joint variability during the performance of a task allows the movement system to be relatively stable when it needs to be, and to be flexible when it needs to adapt to intrinsic or extrinsic changes maintaining the ongoing action [9]. As in the case of the *demi-plié* when it is in preparation for subsequent ballet movements, our findings showed that the variability of the knee angle occurred, causing dissimilarities amongst different performances of the *demi-plié*, depending on the end-goal. These observations suggest that resulting adjustments are primarily under feed-forward control, and even though the differences amongst the *demi-pliés* are clear when plotted in graphs, it remains unseen at the audience’s eyes when the ballet dancer is on stage, not compromising the aesthetic and beauty of the performed movement.

The differences in the *demi-plié* performance depending on its end-goal can also be explained in terms of learning multiple patterns of its execution, considering multiple CNS variables representing these multiple required patterns. Previous research [10] argues that learning multiple patterns is related to the notion of recall, defined as the selective activation of a learned coordination pattern under the influence of the same or similar environmental information as was present during learning. Therefore, as the environmental information need not be exactly identical to one of the memorized patterns, recall in this sense resembles pattern recognition in models of perception. In a straightforward generalization, our findings suggest that the ballet dancer learns multiple patterns of execution of the *demi-plié* when it comes to performing subsequent complex ballet movements.

For a global internal model to adapt to different sensorimotor contexts, the CNS must learn the properties of tools and environments whenever they are altered, even if these properties have been learned previously [5]. Moreover, if the CNS has already learned how to perform the *demi-plié* movement, the change on its end-goal may be facilitated by combining multiple ways to execute it in anticipation of the next movement. This interpretation assumes that separate internal models are learned for different environments and also permit mixtures of internal models to cope with a single environment or task.

The present findings suggest that the notion of multiple internal models can be extended to different classes of transformations, namely, dynamic and kinematic transformations expressed in different interlimb distinct coordination patterns of the *demi-plié* performance when it is in preparation for subsequent ballet movements.

6.5 CONCLUSION

The *demi-plié* movement of classical ballet revealed different coordination patterns depending on its end-goal.

Kinematic analysis showed differences at the interlimb level through the knees joint angles and their angular velocity measurements, illustrating different variability patterns for each *demi-plié* condition.

Similar coordination patterns were found for similar ballet movements, such as the case of the simple *demi-plié* and the *demi-plié* prior to *relevé* and the *demi-plié* prior to jumps.

Due to the unique characteristic movement of the *pirouette*, the *demi-plié* prior to *pirouette* displayed a unique coordination pattern.

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CHAPTER 7:

Scientific Production - Article 4

Muscular activation during the *demi-plié* movement in its different roles in classical ballet

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ABSTRACT

Demi-plié is a coordinated ballet movement involving a continuous bend of the knees, keeping hips turned out and heels grounded. It consists of descending and ascending phases, the latter often preparing for the next move. The *demi-plié* end-goal may influence its muscular activation patterns. Nine classical dancers performed the *demi-plié* itself and prior to other ballet movements such as: *pirouette en dehors*; *relevé*; *sauté*; and *sissonne fermée de côté*. Muscular activation of the *tibialis anterior*, *gastrocnemius medialis*, *rectus femoris*, and *biceps femoris* were measured using surface electromyography. All muscles showed significant differences across the ballet movements; however, the BF was the least active muscle and behaved similarly across experiments. Effect sizes (ES) of selected statistical metrics showed large variability depending on the movement. Nonetheless, the direction of the ES was positive in all experiments, with distinct behavior of muscular activation depending on the *demi-plié* end-goal. The *tibialis anterior* was the only muscle that showed significant differences for all experiments. Specific muscular demands depending on the *demi-plié* end-goal such as *pirouettes* and jumps, happen with the attempt to anticipate the next motor action, suggesting potential applications for refining ballet training and rehabilitation practices to enhance performance and prevent injuries.

Keywords: *demi-plié*; electromyography; movement pattern; ballet movement

7.1 INTRODUCTION

Classical ballet is a highly expressive art form that requires significant physical demands from the dancers, especially in terms of their lower limb strength and control. The *demi-plié* movement, which involves bending the knees while maintaining an upright posture, is a fundamental technique in classical ballet that is used extensively in various ballet movements.

The *demi-plié* movement consists of two phases: descending phase and ascending phase. During the descending phase, the dancer lowers their body by flexing the knees and ankle joints simultaneously, with external rotation of the hips, while maintaining heels on the floor and minimum pelvic tilt with an upright posture (Coker et al., 2015; Kim and Kim, 2016). The descending phase is critical for developing lower limb strength, as it requires the activation of several muscles at the same time. The ascending phase of the *demi-plié* is initiated by the upward movement of the hip, which extends the thighs, knees and ankle joints simultaneously. The muscles of the lower limb work to accelerate the upward movement and control the ascent. The ascending phase is often in preparation for subsequent movements (Imura and Iino, 2017, 2018).

Research in classical ballet has evolved in the past decades (Quadrado et al., 2022), with the number of publications growing every year, and a baseline of knowledge being created in terms of studies regarding ballet movements, comparisons about modalities, and comparisons amongst levels of expertise and sex. Sensing technology such as surface electromyography (EMG) has the strong potential to reveal aspects of movement dynamics and how the muscles coordinate to express the aesthetic and beauty seen in classical ballet.

Previous research has used EMG in studies regarding the *demi-plié,* describing the pattern of muscular activation of the lower limb in this movement (Trepman et al., 1994, 1998; Lin et al., 2013), and also the muscular activation of other ballet movements such as complex jumps amongst skilled ballet dancers (Lepelley et al., 2006). Trepman and colleagues (1994) have also made comparisons of the *demi-plié* performance between classical ballet dancers and modern dancers, highlighting the differences in the muscular activation patterns depending on the dance modality. Kim and Kim (2016) have compared the muscular activation patterns between the *demi-plié* and *relevé* (heel rises) with simple heel raises and squats, clarifying the differences between these movements due to the technical expertise required in classical ballet. Lee and colleagues (2012) made comparisons between injured versus non-injured ballet dancers during the execution of a ballet movement that requires lateral body displacement (*sissonne fermée de côté)*, showing that injured dancers presented higher muscular co-contraction in the non-dominant leg. To the best of our knowledge, there are no studies analyzing the hypothetical differences on the *demi-plié* muscular activation when linked to other ballet movements. For instance, the *demi-plié* may present differences in coordination when it is in preparation for a vertical jump or for a turn, as the end goals of those movements are different.

In the present study, we aimed to find the differences in muscular activation during both phases of the *demi-plié* when it is performed by itself and when it is in preparation for subsequent movements such as: vertical jumps (*sauté*); heel rises (*relevé*); outward turn (*pirouette en dehors*); and lateral body displacement (*sissonne fermée de côté).* We hypothesized that the muscular activation of the *demi-plié* would differ according to the end-goal.

7.2 METHODS

7.2.1 Participants

Nine classical ballet dancers (6 females, 3 males), aged between 20 to 34 years old (mean ± standard deviation (SD) of 23.6±4.6 years old), with a minimum of six years (mean±SD of 11.3±4.6 years) of experience in classical ballet and currently active in the modality, training a minimum of 5 hours per week (mean±SD of 14.7±11.4 hours) participated voluntarily in the experiment. The sample size was estimated using F-tests (ANOVA, Repeated Measures, Within Factors) for 1 group and 5 measurements, an alpha error probability of 0.05, a beta error probability of 0.20, non-sphericity correction $\varepsilon = 1$, effect size (ES) = 0.4, and a correlation amongst measures of 0.50, which provided a total sample size of 9 subjects. This procedure was performed using the GPower software (version 3.1, Universität Düsseldorf, Germany).

Participants' demographics varied between college students (characterized as pre-professional dancers n=3), professionals currently working in professional dance companies (n=3), and amateur dancers, practicing ballet classes as a hobby or for leisure (n=3). All participants provided limb dominance information by answering which leg they would prefer to kick a ball and which hand they would prefer to throw and catch an object, and only one female participant showed to be left-side dominant. Participants were healthy and had not suffered any injury within six months prior to the experiment date. All participants provided signed informed consent for voluntary participation in the experiment. This research was approved by the local ethical committee, in accordance with the latest version of the Declaration of Helsinki for experiments in humans.

7.2.2 Data collection

EMG data was recorded using two portable devices (BITalino MuscleBIT, Plux Biosignals) (Batista et al., 2019), one for each leg, attached to a small pouch placed around the waistline of the participants. Each device had four channels, each connected to a twined cable and snap buttons for pairs of surface disposable electrodes (Ag/AgCl). Electrode pairs were placed in a bipolar configuration along the longitudinal axis and belly of the selected muscles: *tibialis anterior* (TA); *gastrocnemius medialis* (GM); *rectus femoris* (RF); and the long head of the *biceps femoris* (BF) muscle, bilaterally for all the participants. The inter-electrode distance was 1.5 cm. The correct placement was confirmed by manual muscle testing performed by an experienced researcher, and visual inspection of the raw EMG signal by the experimenter. The ground electrode was placed over the right lateral malleolus of all participants. The same researcher was responsible for the placement of electrodes in every participant. After familiarization, participants reported no serious impediment, of either electrodes or cables, in performing the referred ballet movements. The EMG devices were connected via Bluetooth to a computer, and data was captured at a sample rate frequency of 1000 Hz. Before placing the electrodes, the skin was shaved when needed, cleaned with alcohol, and slightly abraded to further reduce skin resistance, in accordance with the SENIAM recommendations (Hermens et al., 2000).

7.2.3 Experimental design

Participants performed the *demi-plié* and the *demi-plié* in preparation for four subsequent movements, such as: *sauté*; *relevé*; *pirouette en dehors*; and *sissonne fermée de côté.* The sequence of movements was randomly determined for each participant. As a matter of standardization of the experimental design, all movements were performed in the “first position”, well-known in classical ballet for both feet and arms, which is characterized as an external rotation of the thighs and legs, with both feet pointing outward, and arms elevated at the belly button height, with forearms slightly supinated and rounded with the hands facing the dancer. Participants had warmed up prior to measurements and testing.

The researcher provided clear verbal instructions for the descending phase of the *demi-plié*, which was set to a 64-bpm metronome cadence, to be performed in two beats. This was followed by the preparatory phase for the ascending phase that seamlessly blended into the following movement.

Participants completed five cycles of each experimental condition, which were performing the *demi-plié* itself and in preparation for four other subsequent ballet movements aforementioned. Based on a preliminary trial, five rounds of each experimental condition were determined to be optimal to avoid muscle fatigue, since participants had to perform five different experimental conditions in a single session. Each experimental condition was separated by a five-minute rest period for all participants. Participants wore soft ballet shoes, typical for ballet practice. The experiment was conducted in a room with a linoleum floor, often found in ballet studios and theaters, and dimmed lighting to eliminate distractions or disturbances. The entire experimental session lasted about one hour.

7.2.4 Data analysis

The EMG signals were recorded using the OpenSignals software (Plux Biosignals), in which the starting time of the descending phase of the *demi-plié*, and the end of the ascending phase, when the *demi-plié* would then be fused to the subsequent movement, were identified. The timing of muscle contraction was selected for both phases using the muscle activation pattern observed in the isolated *demi-plié* performance as the reference. As the metronome was set at 64 bpm, the time of execution of the *demi-plié* was two beats of the metronome for the descending phase, and two beats for the ascending phase, then linked to the subsequent movement. However, depending on the subsequent movement, muscle activation could differ, possibly in anticipation for the next movement, so the ascending phase was limited based on the time set by the metronome, which often coincided with the deactivation of the TA in the ascending phase, as observed in the isolated *demi-plié*.

EMG signals were visually inspected for artifacts and noise. We have applied a low-pass filter at 450 Hz, high-pass filtered at 10 Hz, rectified and linear envelope low-pass filtered at 2.5

Hz (Nielsen et al., 1994; Barsotti et al., 2018), using a custom-designed MATLAB routine (version R2022b, MathWorks Inc., USA), also used for plotting the data.

Data was further analyzed on a different custom-designed MATLAB routine, taking the duration of the descending and ascending phases of the *demi-plié*, and selected metrics such as: integral; mean; standard deviation (SD); kurtosis; skewness; minimum contraction; quartiles at Q50, maximum contraction; and interquartile range (IQR), for all the selected muscles, bilaterally for all the participants and for all movements.

The integral metric was used to normalize the EMG signals by taking the simple *demi-plié* as a reference and calculating the integral values as expressed in Equation 1.

Equation 1: EMG dataset normalization. x represents the *demi-plié* prior to subsequent movements.

$$[(integral\ of\ x - integral\ simple\ demipli\acute{e}) \div integral\ simple\ demipli\acute{e})] \times 100\%$$

Statistical analysis was performed to the normalized data, as well as to investigate potential differences in the referred metrics of the *demi-plié* in all five movements for each leg separately, using the SPSS software (IBM SPSS version 29.0.0). Descriptive analysis was conducted alongside non-parametric tests such as related-samples Friedman's two-way analysis of variance and Wilcoxon Signed rank tests, to assess differences amongst the five different movements, and pairwise comparisons for each pair of movements. Furthermore, the independent-samples Mann-Whitney U test was conducted for comparing both legs to examine any significant differences in metrics between them. Results indicated that both legs exhibited similar behavior.

Based on these findings, the aforementioned descriptive analysis was repeated. This time, both legs were considered for computing subsequent variables such as: duration; integral; SD; kurtosis; skewness; Q50; maximum contraction; and IQR. This analysis was performed for all five movements and for each selected muscle. The significance level of 5% was considered. Significance values were adjusted by the Bonferroni correction for multiple tests. Finally, Cohen's d effect size (ES) was analyzed, taking into consideration the mean and SD values for each selected muscle and the comparison between them. Furthermore, we have made comparisons amongst the four muscles for each experimental condition.

7.3 RESULTS

7.3.1 Analysis of each muscle for all experimental conditions

The statistical analysis did not show significant differences for the normalized EMG data.

The envelope of the EMG signal shows the intensity of the amplitude of muscle contractions, as well as how long a certain muscle remains activated during the movement execution, which was possible to observe for each of the four muscles during the full experimental session of the *demi-plié* performance. By visually inspecting the plots displayed in Figure 1, it is possible to observe the distinctions in muscle activity throughout time. As seen in Figure 1 A), the TA muscle showed the highest muscular activation throughout the experiments that can be seen through the amplitude values in mV, and the BF muscle the lowest, in contrast. However, TA and GM are agonist-antagonist muscles, and they both display similar amplitudes, but distinct patterns. On the other hand, RF and BF are also agonist-antagonist muscles, and their behavior throughout the experiments cannot be seen as analogous. The amplitude and frequency of muscle activity in the RF is higher than seen in the BF. The data contained in Figure 1 is from a randomly selected participant.

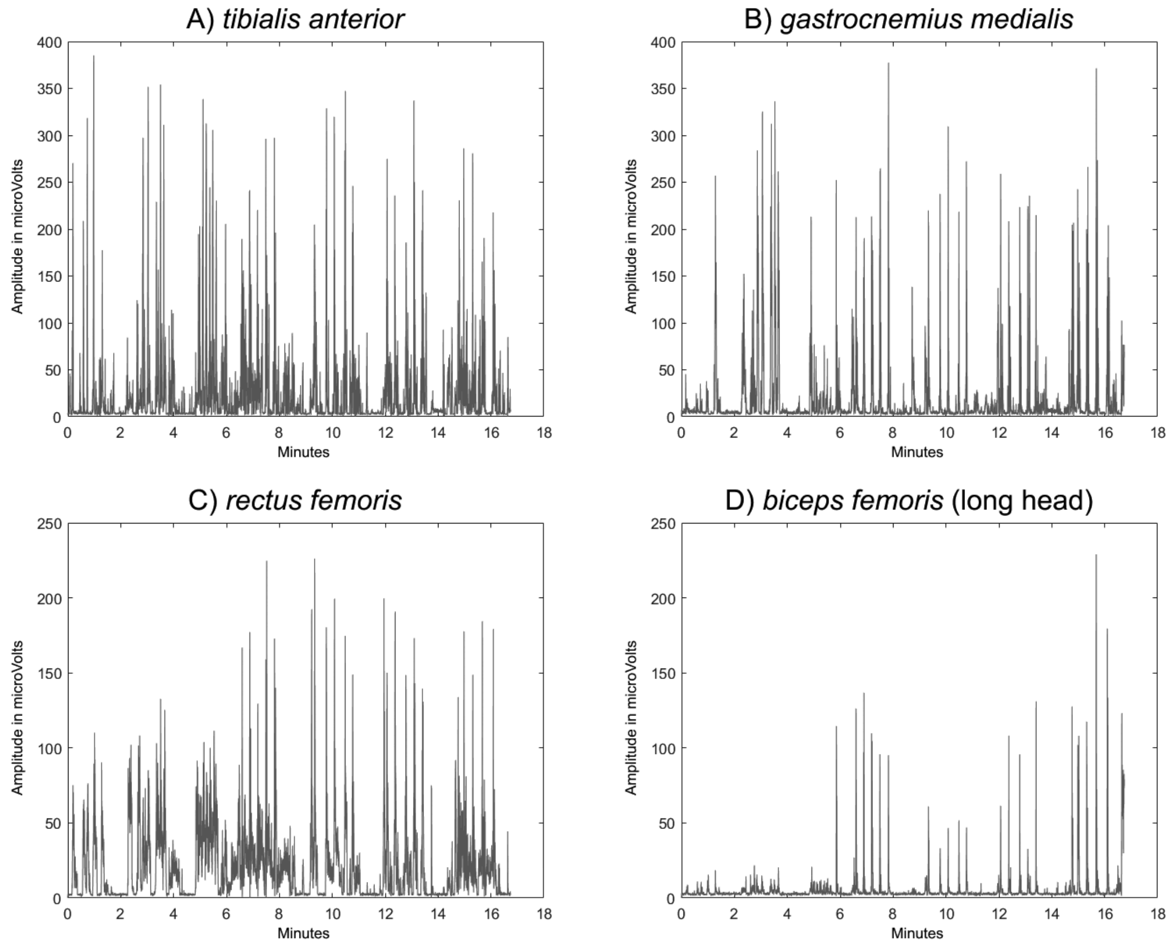


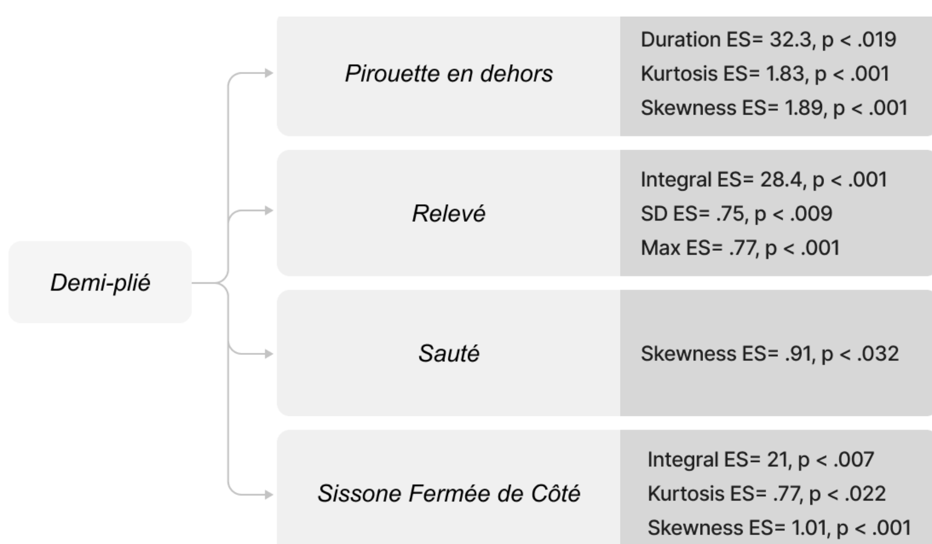
Figure 1: EMG envelope signal of the right leg for all movements performed in random order by an exemplar participant. A) *tibialis anterior*; B) *gastrocnemius medialis*; C) *rectus femoris*; D) *biceps femoris* (long head). The order of execution was *relevé*, *demi-plié*, *pirouette en dehors*, *sauté*, and *sissonne fermée de côté*. Axis X displays the time in minutes. Axis Y displays the amplitude of the EMG signal in microVolts.

Each muscle was analyzed independently, for all experiments, and Table 1 outlines the significant differences observed between the *demi-plié* and the *demi-plié* performed prior to each subsequent movement. Figure 2 depicts a diagram that illustrates for each muscle their significant differences across the experiments. The BF muscle did not show significant differences when compared to the simple *demi-plié*. The RF muscle showed significant differences in both the *demi-plié* prior to *relevé* and *sauté* when compared to the simple *demi-plié*, but not when it was compared to the *demi-plié* prior to *pirouette en dehors* and *sissonne fermée de côté*. Both muscles TA and GM showed significant differences in the *demi-plié* prior to all movements when compared to the simple *demi-plié*.

Table 1: EMG metrics displaying significant differences between the *demi-plié* and the *demi-plié* prior to *pirouette en dehors*, *relevé*, *sauté*, and *sissonne fermée de côté* for each muscle regarding the difference in the metric (Δ), p-values, and effect sizes (ES). TA: *tibialis anterior*; GM: *gastrocnemius medialis*; RF: *rectus femoris*.

	***Demi-plié* prior to**							
EMG	***Pirouette en dehors***		***Relevé***		***Sauté***		***Sissonne fermée de côté***	
metric	Muscle	Δ; p-value; ES	Muscle	Δ; p-value; ES	Muscle	Δ; p-value; ES	Muscle	Δ; p-value; ES
duration (ms)	TA	199; <.019; 32.3	-	-	GM; RF	185; <.003; 0.98 157; <.001; 1.17	-	-
integral ((µV.s)	-	-	TA; GM	3201; <.001; 28.4 5010; <.022; 0.65	-	-	TA; GM	3915; <.007; 21 3909; <.003; 0.88
SD (µV)	-	-	TA	9.8; <.009; 0.75	-	-	GM	12; <.002; 0.79
kurtosis	TA	2272; <.001; 1.83	RF	2.7; <.044; 0.79	RF	2.4; <.005; 0.26	TA	2.8; <.022; 0.77
skewness	TA	1061; <.001; 1.89	RF	0.5; <.022; 0.66	TA; RF	1.9; <.032; 0.91 0.5; <0.22; 0.72	TA	9.2; <.001; 1.01
Q50 (µV)	-	-	-	-	-	-	GM	25; <.032; 0.05
max (µV)	-	-	TA	37.2; <.001; 0.77	-	-	-	-
IQR (µV)	-	-	-	-	-	-	GM	18.4; <.011; 0.76

A) *tibialis anterior*



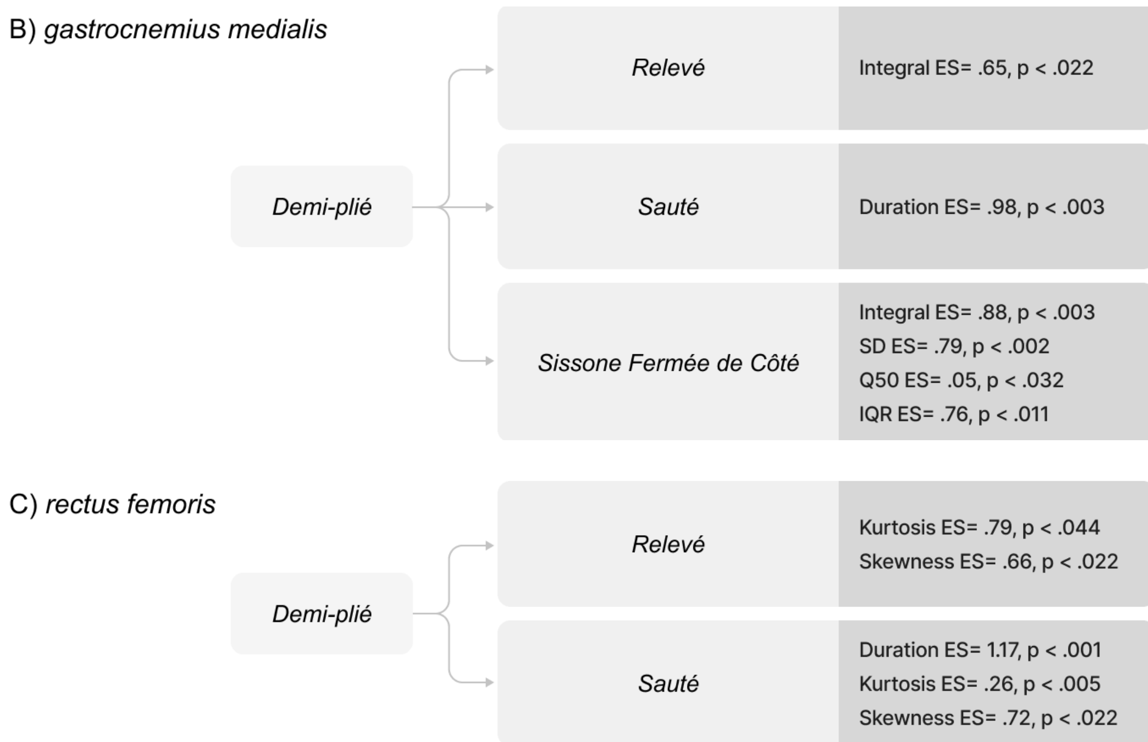


Figure 2: Diagram of each muscle and their significant differences regarding the statistical metrics for each experimental condition when compared to the isolated *demi-plié*. A) *tibialis anterior*; B) *gastrocnemius medialis*; C) *rectus femoris*. ES: effect size.

We have made comparisons amongst the four muscles regarding each experimental condition, and Figure 3 depicts the boxplot of such comparisons. The *demi-plié* prior to *pirouette en dehors* (Figure 3B) and prior to *sissonne fermée de côté* (Figure 3E) display significant differences in the GM and BF amongst all the muscles and amongst each other, whereas the simple *demi-plié* (Figure 3A) displays significant differences only for the BF. The other experimental conditions did not show significant differences amongst the muscles (Figure 3C and D).

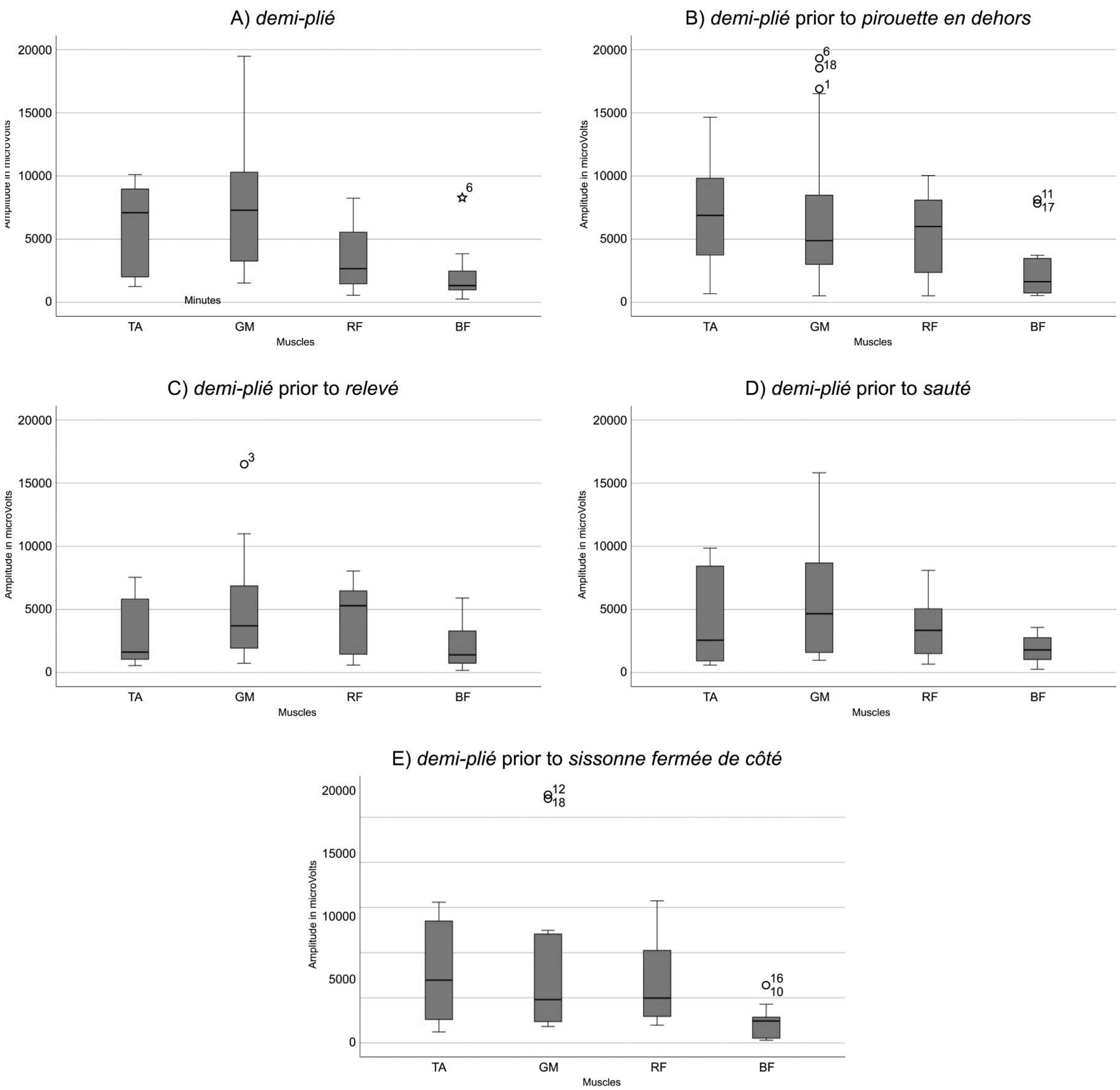


Figure 3: Boxplots of the EMG integral for muscles *tibialis anterior* (TA), *gastrocnemius medialis* (GM), *rectus femoris* (RF) and *biceps femoris* 'long head' (BF) of all participants. Each muscle displays respective values for each experimental condition. Numbers in the plot represent muscle activation not typical of the rest of the data, displaying significant differences. A) *demi-plié*: the BF showed significant differences when compared to other muscles; B) *demi-plié* prior to *pirouette en dehors*: the muscles GM and BF showed significant differences when compared to the other muscles and with each other; C) *demi-plié* prior to *relevé*: the GM showed significant differences when compared to the other muscles; D) *demi-plié* prior to *sauté*; E) *demi-plié* prior to *sissonne fermée de côté*: the: the muscles GM and BF showed significant differences when compared to the other muscles and with each other. Axis X displays the muscles. Axis Y displays the amplitude of the EMG signal in microVolts.

7.3.2 Analysis of the effect size

Cohen's d ES measures the difference between two means divided by a pooled SD. This ES measure gives an indication of how many SD separate the two group means, which in the present study, it was expressed by the difference between the isolated *demi-plié* with each of the other experimental conditions. In the present study, the ES presented values ranging from very small to huge depending on the metric and muscle for each experimental condition. Additionally, all values of ES were positive, suggesting that when the *demi-plié* has an end-goal, the muscle is more actively engaged or undergoes more strain than when it is activated for the execution of an isolated *demi-plié*.

7.3.2.1 Tibialis Anterior

Effect sizes of huge magnitude values were found for the TA muscle regarding the *demi-plié* prior to *pirouette en dehors* when compared to the simple *demi-plié* for the metrics duration, kurtosis, and skewness. Also, in the metric integral regarding the *demi-plié* prior to *relevé* and prior to *sissonne fermée de côté*, and in the skewness regarding the *demi-plié* prior to *sauté.* For the other metrics regarding the other movements, the TA showed large ES values (Table 1; Figure 2A).

7.3.2.2 Gastrocnemius Medialis

The GM muscle showed medium ES in the metric integral regarding the *demi-plié* prior to *relevé*, and in the metrics SD and IQR regarding the *demi-plié* prior to *sissonne fermée de côté.* Large ES was found in the metric duration regarding the *demi-plié* prior to *sauté,* and in the integral regarding the *demi-plié* prior to *sissonne fermée de côté.* Lastly, a very small ES was found in the metric Q50 *sissonne fermée de côté* (Table 1; Figure 2B).

7.3.2.3 Rectus Femoris

The RF muscle showed medium ES in all the significant metrics regarding the *demi-plié* prior to *relevé,* but huge ES in the duration of the *demi-plié* prior to *sauté,* small ES in the kurtosis, and medium ES in the skewness of this same movement (Table 1; Figure 2C).

7.4 DISCUSSION

The aim of the present study was to test the hypothesis that the *demi-plié* movement presents different muscular activation patterns depending on the end-goal. We analyzed the *demi-plié* movement itself and in preparation of four subsequent movements (i.e. *pirouette en dehors*, *relevé*, *sauté*, and *sissonne fermée de côté*).

Each muscle was analyzed individually, for each experimental condition, and the results showed significantly different patterns of muscular activation for all muscles, except for the BF. A possible explanation can be due to the BF activity being primarily in the descending phase of the *demi-plié* (Padulo et al., 2013), which appeared consistent across all experimental conditions. Additionally, Gregoire et al. (1984) described the muscular activation of a squat movement prior to a vertical jump, arguing that the movement is controlled in a proximodistal manner. In other words, the preparation for a vertical jump is controlled by the lower limb muscles respecting a certain order of activation that comes from the pelvis, then the knees, and finally the ankles. The authors reported that the hamstrings are active just before take-off, and in our experiments, the BF was the least active muscle that in fact behaved similarly across conditions. Hence, there were no significant differences in the BF performance when the *demi-plié* had different end-goals.

The TA muscle showed the most significant differences in regards to all metrics and experimental conditions. In the *demi-plié* ballet movement, especially in its ascending phase, the TA is already contracted to its full capacity in order to propel the body against gravity

(Trepman et al., 1994). When it comes to the ES analysis, the TA was the muscle that showed the most frequent huge ES values, showing its remarkable function in the performance of the *demi-plié* when this movement has different end-goals, especially in the execution of the *demi-plié* prior to *pirouette en dehors*, which happens to be a very complex movement. The *pirouette en dehors* involves a single-leg movement with pivotal motion that reflects an outward turn, while the opposite leg undergoes external rotation with hip and leg flexion, and the tip of the hallux toe touches the medial part of the opposite knee. Imura and Iino (2018) have studied the kinetics involved in the revolution of a *pirouette*, describing the angular momenta of the hips and upper body in preparation for the revolution. However, there were no interpretations of the lower body behavior, and the present study potentially complements the research performed by Imura and Iino in 2018, adding EMG findings that increase the baseline of knowledge of classical ballet. Even though we have only analyzed the *demi-plié* prior to a *pirouette*, it would be interesting to further analyze each leg separately, perhaps incorporating the use of a force platform to measure the center of pressure and ground reaction forces during the *demi-plié* prior to a *pirouette en dehors*, providing additional insights into the movement dynamics.

The GM muscle had the highest differences in the *demi-plié* prior to *sissone fermée de côté*, but also presented significant differences in the duration of contraction in the *demi-plié* prior to *sauté*, both displaying a large ES. Both *sissone fermée de côté* and *sauté* demand plyometric forces to execute the jump, requiring full extension of both legs simultaneously. Čoh and colleagues (2015) have shown that the GM displayed the highest peaks of contraction just before take-off. However, in the present study, we cannot precise the moment of highest peaks of contraction, as we have only observed the overall muscle behavior during the execution of the simple *demi-plié* and the *demi-plié* with different end-goals, knowing that the ascending phase of the *demi-plié* is fused to the subsequent movement. Moreover, when a ballet dancer performs a jump, the aesthetic and technique of classical ballet require that both legs are fully extended in the air and with both feet in plantarflexion, which means that the GM remains activated after take-off. It makes sense that this muscle displays distinct patterns when the *demi-plié* is in preparation for jumps.

The RF muscle is a biarticular muscle that performs both leg extension and hip flexion, so it was expected that this muscle would not show strong activity during the *demi-plié*, corroborating our findings with the ones from Trepman and colleagues (1994), who were the first researchers to study the EMG technique to analyze muscular activity in the *demi-plié* movement. The authors also made comparisons between classical and modern dancers, whereas in the present study, we have solely analyzed classical dancers. However, when the *demi-plié* movement is fused to the next motor action and the legs begin to extend, the RF showed significant differences when the *demi-plié* is in preparation for a *relevé*, which requires that both legs are fully symmetrically extended in a closed kinetic chain. Additionally, the RF showed significant differences when the *demi-plié* is in preparation for a *sauté*, which is a vertical jump requiring both legs symmetrically extended while in the air. The RF duration of contraction in the *demi-plié* prior to *sauté* had a huge ES, whereas the other metrics presented medium values of ES for both movements, revealing how the RF can be important when the subsequent ballet movement demands symmetry from both legs.

Our study was not free from limitations, for instance, the sample size, which was small and with classical dancers from different levels of expertise. It would be interesting to have a larger sample and analyze the EMG data from the participants and make comparisons amongst different levels of expertise. Furthermore, according to a systematic review performed by our group, regarding sensing technologies to capture and analyze ballet movements' data, we concluded that two or more techniques will increase data reliability (Quadrado et al., 2022). In the present study we have only analyzed EMG data, and it would be suggested to incorporate additional sensing technologies such as force platforms and electroencephalography, in order to measure ground reaction forces and brain activity, respectively.

The implications of our study are potentially significant for the refinement of training paradigms and rehabilitation strategies within the context of ballet. Ballet coaches, in particular, may find these insights invaluable as they strive to enhance the efficacy of training sessions and rehearsals. By incorporating our findings, they could more effectively mitigate the risks associated with muscle fatigue and the consequent likelihood of injury. This proactive approach to training could fundamentally transform the traditional methodologies employed in ballet education, promoting a more sustainable practice that prioritizes the well-being and longevity of dancers.

Furthermore, the relevance of our results extends to clinical settings, where physiotherapists and rehabilitation specialists may harness the detailed understanding of ballet movements provided by our study. This could facilitate the design of targeted rehabilitation routines that employ ballet-specific movements as therapeutic exercises. Such routines could be particularly beneficial in addressing and ameliorating the frequent, yet often minor, injuries incurred by dancers during their rigorous daily practices. Overall, our study contributes to a more nuanced understanding of ballet mechanics, offering a dual benefit of enhancing performance while reducing injury risk, thereby supporting the health and career sustainability of dancers.

7.5 CONCLUSION

Each muscle presented a different muscular pattern of activation depending on the end-goal of the *demi-plié*. It seems that the execution of the *demi-plié* is directly related to the subsequent ballet movement, so the muscles will display a distinct behavior already in the *demi-plié*, as an anticipatory response to the next motor action.

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CHAPTER 8:

Scientific Production - Article 5

Brain activation of the sensorimotor cortex during the *demi-plié* movement in its different roles in classical ballet

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Status: Under review in Dance Research

ABSTRACT

Demi-plié is a ballet movement involving a continuous bend of the knees, keeping the thighs externally rotated and heels on the ground. Task goals may influence brain activation patterns. Twelve classical dancers performed the *demi-plié* itself and prior to other ballet movements such as: *relevé*; *sauté*; *sissonne fermée de côté*; and *pirouette en dehors*. Electroencephalography measures were taken from the primary motor area, premotor cortex, and supplementary motor area during the movement performance. Significant differences were found amongst the *demi-plié* prior to jumps and turns. The sensorimotor cortex seems to display different orders of activation depending on the *demi-plié* end-goal.

Keywords: *demi-plié*; electroencephalography; cortical activity; movement pattern; ballet movement

8.1 INTRODUCTION

Demi-plié is a ballet movement that involves bending the knees with the lower limb in external rotation (turnout) and heels on the ground while maintaining an upright posture, being foundational in classical ballet technique, and extensively used in preparation for other ballet movements.

The *demi-plié* movement consists of two phases: descending and ascending. During the descending phase, knee flexion and ankle dorsiflexion happen simultaneously, critical for developing lower limb strength, and requiring the activation of several muscles at the same time. The ascending phase of the *demi-plié* is initiated by the upward movement of the pelvic complex, extending the thighs, knees, and ankle joints simultaneously. The muscles of the lower limb work to accelerate the upward movement and control the ascent, which is often in preparation for subsequent ballet movements, such as jumps, turns or heel rises [1-3].

Interlimb coordination and anticipatory adjustments for subsequent movements are paramount to performing a correct *demi-plié.* Notwithstanding, interlimb coordination might change due to different end-goals with potential consequences at the brain level. Previous research [4] using electroencephalography (EEG) in ballet dancers, has found that the long-term specialized use of the muscles induces adaptation of the strategy used by the central nervous system to perform a particular muscular contraction, which suggests that the *demi-plié* movement execution may present differences at the cortical control depending on its end-goal. Therefore, we hypothesize that cortical activity will differ depending on the end-goal, i.e. when the *demi-plié* is in preparation for different subsequent movements.

Scalp EEG is one of the most frequently used neurophysiological methods, providing information about changes in electrical potential across the brain with high temporal resolution. Typical EEG setups measure cortical activity across multiple points on the scalp. The source location of the electrode's position on the brain cortex has corresponding relationships with motion parts and motion types of the body, which makes it possible to characterize cortical activity associated with movement by EEG signal analysis [5]. Lower limb areas are mainly associated with the upper portion of the motor cortex, near the medial surface of the brain.

In EEG analysis, brain wave frequencies are categorized into different bands, each associated with different cognitive processes [6,7]. The frequencies alpha (8-12 Hz), low-beta (13-18 Hz), and high-beta (18-30 Hz) are amongst these bands, and their relationship with lower limb voluntary movement is an area of interest in neuroscience and neurophysiology [8,9]. Alpha rhythm is known to be indicative of a relaxed, yet alert state and is often prominent when the individual is in a state of wakeful rest with their eyes closed. Beta rhythms are suggested to play a role in maintaining the current motor state, which is essential for movements involving the lower limbs [10,11]. Low-beta activity is typically associated with active engagement in motor tasks. In particular, in tasks requiring anticipation of movement, as in the case of the *demi-plié* in preparation for subsequent ballet movements, low-beta activity might be indicative of the brain's processing of this information [12]. Moreover, the high-beta frequency band is also linked with higher-level cognitive processes involved in human movement, such as attention, working memory, and the integration of sensory feedback necessary for precise motor adjustments.

The primary motor cortex (M1) is central to the direct execution of movement, especially in controlling lower limb movements. Located in the precentral gyrus of the frontal lobe, M1 contains neurons that project directly to the spinal cord, influencing muscle contractions and movement execution. This cortical area has a somatotopic organization, meaning that specific regions correspond to different parts of the body, with a considerable portion dedicated to the control of the lower limbs. When initiating a movement, M1 becomes actively involved in sending precise motor commands to the relevant muscles, ensuring accurate execution of actions. M1 is particularly crucial for the fine-tuning of movements, allowing for detailed and nuanced control of the lower limbs, which is essential for tasks requiring precision and coordination, such as walking, running, or performing complex tasks that involve the legs [13,14,15].

The premotor cortex (PMC) plays a role in the planning and preparation of movements, acting as a bridge between the intention to move and its execution [16]. Situated anteriorly to the M1, the PMC integrates sensory information with motor plans, preparing the body for movement. It is actively involved in the spatial and temporal organization of movements, essential for coordinating complex motions, especially in the lower limbs. The PMC thus contributes to the selection of appropriate motor plans and sequences of actions, working closely with other brain areas to ensure that movement commands are carried out smoothly and efficiently. This area is particularly important for movements that are guided by external cues or require adaptation to changing environments, such as adjusting gait or balance during dynamic activities involving the lower limbs [16,17].

The supplementary motor area (SMA) is integral to the initiation of complex, sequenced movements, playing a role in the higher-level planning and execution of motor tasks. Located on the medial surface of the frontal lobe, the SMA is important for the coordination of bilateral movements and integration of movements of different body parts, including the lower limbs. It is involved in the initiation of movements, particularly those that are internally generated or involve a sequence of actions. The SMA works in conjunction with the M1 and PMC, contributing to the smooth execution of movements by ensuring that the various components of a motor task are properly sequenced and timed. Its contribution is vital for activities that require coordination of both lower limbs, such as intricate footwork in dance or sports [16,17].

As such, motor coordination is not managed by specific brain areas but rather requires a general increase in activation of a complete motor network which is distributed across cortical and subcortical regions. Therefore, due to different planning demands we expect to observe different patterns of cortical activation in the M1, PMC, and SMA, depending on the end-goal of the *demi-plié*. In particular, we expect to observe differences in the brainwave frequency bands alpha, low-beta, and high-beta, since those frequencies are related to brain activity associated with movement [5,8,12-17]. To the best of our knowledge, this is the first study that makes use of EEG to analyze brain activation patterns of the M1, PMC, and SMA during the performance of a classical ballet movement.

8.2 METHODS

8.2.1 Participants

Ten female and two male classical ballet dancers, aged between 20 and 45 years old, with a minimum of six years of experience in classical ballet and currently active in the modality, participated in this study. The sample size was determined using F-tests (ANOVA, Repeated Measures, Within Factors) for 1 group and 5 measurements, an alpha error probability of 0.05, and a beta error probability of 0.20, which provided a total sample size of 12 subjects. This procedure was performed using the GPower software (version 3.1, Universität Düsseldorf, Germany).

The demographic profile of the participants ranged from pre-professional dancers (n=5) to professionals employed by dance companies (n=3), and amateurs taking ballet for recreation (n=4). Everyone indicated their dominant limb by specifying which leg they would use to kick a ball and which hand they would prefer for throwing and catching an object; however, all participants declared to be right-side dominant. Participants were healthy and had not suffered any injury within six months prior to the experiment date.

All participants provided signed informed consent for voluntary participation in the experiments. The research was approved by the local Ethical Committee, in accordance with the latest version of the Declaration of Helsinki for experiments in humans.

8.2.2 Data collection

In the present study, brain cortical activity was recorded using EEG (ENOBIO® EEG Systems, Neuroeletrics), with 8 channels and a sampling rate frequency of 500 Hz. Dry electrodes were placed using a neoprene cap over the motor areas: C3; C1; Cz; C2; C4; F3; Fz; and F4, according to the international extended 10-10 system [16], which offers a finer resolution including C1 and C2 (Figure 1). Electrodes were placed on the head of the participants with reference to anatomical landmarks such as the inion, nasion, and left and right pre-auricular points, such that the central electrode Cz is approximately aligned with the vertex.

The source location of each channel was chosen based on its brain functional representation related to voluntary lower limb movement. The M1, PMC, and SMA are important components of the brain's cerebral cortex, each associated with distinct gyri and collectively involved in the control and execution of movements [16,17].

The specific electrodes relevant for capturing M1 activity are C3, Cz, and C4. These are strategically positioned to monitor the left hemisphere (C3), the midline (Cz), and the right hemisphere (C4), respectively. In a more detailed 10-10 system, electrodes C1 and C2 provide finer resolution for M1 activity. C1 is located over the left hemisphere and C2 over the right, both positioned slightly off the midline, being instrumental in capturing neural signals related to voluntary muscle movements of the lower limbs, according to the homunculus representation, especially fine motor actions [16-19].

The relevant electrodes for monitoring PMC activity include F3, Fz, F4, C3, Cz, and C4, combining both the frontal and central regions [18,19].

The most relevant electrodes for SMA activity are Fz and Cz. These midline electrodes are effective in capturing activity of the SMA due to its medial location. Additionally, electrodes C1 and C2 from the 10-10 system, while more directly over the M1, can also pick up some activity from the SMA. This is due to the adjacency of these areas, allowing for the capture of some SMA-related signals, although with less specificity than the midline electrodes [16-19].

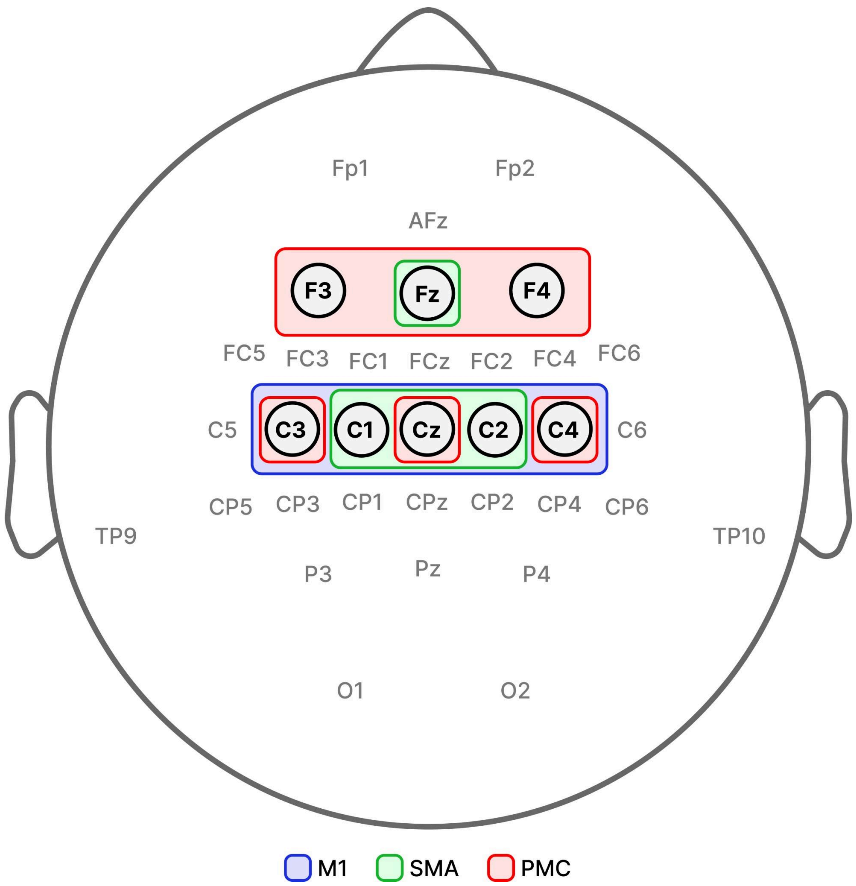

Figure 1: Brain cortical location for each of the 8 electroencephalography dry electrodes placed on the scalp of all the participants in a nylon cap. C3, C1, Cz, C2, and C4 capture cortical activity from the M1 (primary motor area); C1, Cz, C2, and Fz capture cortical activity from the SMA (supplementary motor area), and; C3, Cz, C4, F3, Fz and F4 capture cortical activity from the PMC (premotor cortex area).

8.2.3 Experimental Design

Participants performed the *demi-plié* and the *demi-plié* prior to four subsequent ballet movements, such as: *relevé*; *sauté*; *sissonne fermée de côté*; and *pirouette en dehors*. Participants were allowed to choose their preferred side to perform the *pirouette* revolution, as well as the lateral body displacement in the *sissonne*. The order of ballet movements was randomly selected for each participant, all performed in the "first position" of classical ballet for both feet and arms, which is characterized as an external rotation of the thighs and legs, with both feet pointing outward, and arms elevated at the belly button height, with forearms slightly supinated and rounded with the hands facing the dancer. Participants wore soft ballet shoes, regularly used in ballet training, and had warmed up prior to measurements and testing.

The metronome configured at 64 bpm set the cadence of the descending phase of the *demi-plié*, clearly verbalized by the experimenter to perform the descending phase in 2 beats, and to prepare for the ascending phase that would be fused to the subsequent ballet movement. For the performance of the simple *demi-plié*, participants were instructed to also perform the ascending phase in 2 beats of the metronome.

Participants performed five repetitions of each ballet movement, with varied interval times between repetitions, in order to stabilize the EEG signal after the landing of the *sauté*, *sissonne fermée de côté*, and *pirouette en dehors*. For the simple *demi-plié* and *relevé*, which did not present any impact on landing, therefore not presenting destabilization of the EEG signal, a protocol of 4 beats of the metronome as intervals between repetitions was followed. The pilot trial showed that five repetitions would be the optimum amount in order to avoid muscular fatigue, as the participants would have to perform five different movements in only one experimental session.

8.2.4 Data Analysis

8.2.4.1 Isolating the demi-plié from the subsequent ballet movements

To understand brain activity during the *demi-plié* in all experimental conditions, we focused on isolating this ballet movement, particularly its descending and ascending phases. We achieved this by synchronizing the movement with the EEG software at the moment the participants initiated the *demi-plié*, marking the transition to subsequent ballet movements. This synchronization was guided by real-time annotations made by the experimenter. Further, we compared the brain activity during the *demi-plié* with that of a simple *demi-plié*, focusing on the descending phase and the start of the ascending phase. It is noted that the end of the ascending phase blends seamlessly into the next motor action, creating a continuous flow. This approach allowed for a detailed study of cortical responses associated with specific stages of the *demi-plié*.

8.2.4.2 Illustrating the demi-plié brain cortical activation

Wavelet analysis in EEG is a mathematical and signal processing technique used to analyze and decompose EEG signals into different frequency components and their respective time-domain representations [20]. It provides a multi-resolution analysis, which means it can reveal both high and low-frequency components of the EEG signals with good temporal localization [20]. In other words, a wavelet spectrogram provides a visualization of how the different frequency components vary over time, which is crucial for understanding dynamic brain activity.

In the present study, wavelet transforms were employed to extract specific frequency bands such as alpha (8-12 Hz), low-beta (13-18 Hz), and high-beta (13-18 Hz). This technique decomposes the EEG signal into its constituent frequency components, enabling the identification of the selected frequency bands within the decomposed signal [21,22]. This process is instrumental in determining the power and distribution of these bands over time, offering a comprehensive view of brain activity [21,22]. Furthermore, the wavelet analysis helped in removing eventual unwanted artifacts and noise from the EEG recordings, enhancing the quality of the data for further analysis. Movement artifacts such as eye blinks and pulsatile were not observed during the execution of the *demi-plié*. A cross wavelet and wavelet coherence toolbox for MATLAB (version R2022b, MathWorks Inc.) [23] was used together with an in-house developed script to process the EEG signals, which were further analyzed for comparisons amongst conditions.

8.2.4.3 Statistical analysis

After extracting the selected frequency bands, the next step was to calculate their relative metrics. This was essential for understanding the role and significance of each brainwave type in the overall brain activity. For instance, the relative activity of alpha waves was measured in comparison to other brainwave frequencies, highlighting their contribution to the selected frequency bands [24, 25]. This relative measurement was achieved by first calculating the power of each frequency band, typically through the squaring of the EEG signal amplitude within each band. This power was then normalized by dividing it by the total power across all frequency bands. Such a metric can offer valuable insights into the proportion and significance of different brain waves in various cognitive states, enhancing our understanding of brain activity associated with movement [26].

Particularly when examining frequency bands such as alpha, low-beta, and high-beta, metrics such as integral, Q50 (median), and IQR (interquartile range) were utilized in the data analysis. The integral of a frequency band, for instance, represents the amplitude within that band, calculated as the area under the power spectral density curve. This metric is significant as it indicates the overall level of activity in a specific band. For example, a high integral in the alpha band can suggest a state of relaxation or meditation, given the association of alpha waves with such states [27]. Additionally, the Q50 and IQR metrics, respectively represent the stability and variability of neural oscillations within that frequency band, providing insights into the dynamics of cortical processing for each movement [27].

Descriptive analysis considered a confidence interval for the mean of 95%. Non-parametric analysis of Friedmann's 2-way ANOVA by ranks were performed for comparing all the five experimental conditions, with pairwise comparisons and Bonferroni *post-hoc* comparisons of significant values. Statistical analysis was performed using the IBM SPSS software (version 28, IBM Inc.).

8.3 RESULTS

8.3.1 Wavelet Analysis

By the visual inspection of the wavelet spectrograms of all participants, it was possible to observe different patterns of brain cortical activation for each *demi-plié* condition in regards to the frequency bands alpha, low-beta, and high-beta and for the different EEG channels (Figure 2).

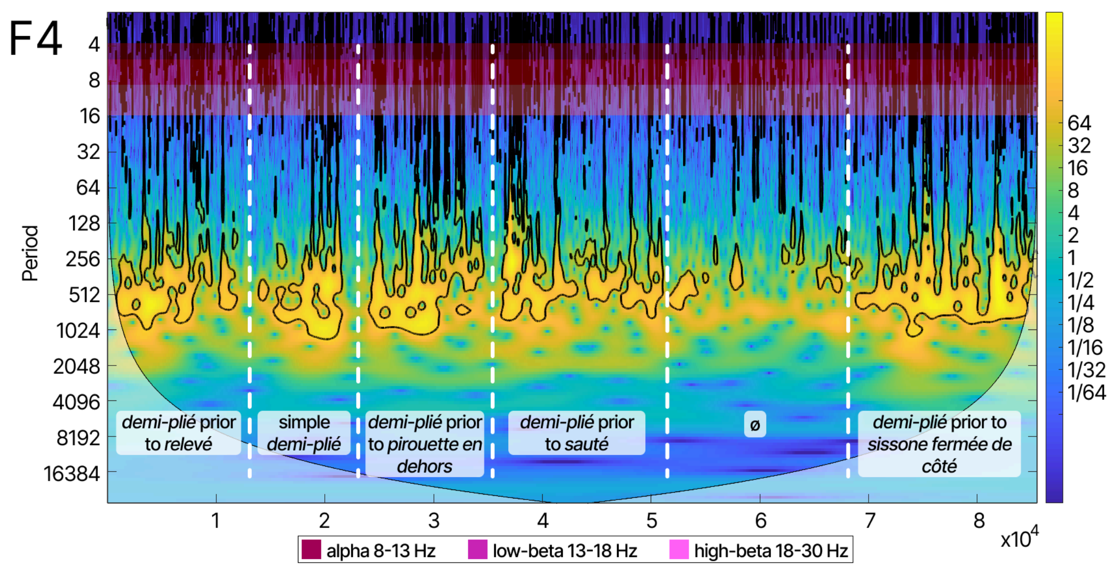

Figure 2: Illustration of a wavelet spectrogram for EEG channel F4 during the execution of the *demi-plié* in the five experimental conditions. The vertical axis represents units of a period, and the horizontal axis represents time in seconds (s). The meaning of colors indicates the amplitude of frequency components at that specific time and frequency. Typically, different colors or shades represent different amplitudes. Darker colors represent higher amplitudes, whereas lighter colors represent lower amplitudes. Selected data from a randomly chosen participant is displayed. The order of movement performance was: 1) *demi-plié* prior to *relevé*; 2) simple *demi-plié*; 3) *demi-plié*

prior to *pirouette en dehors*; 4) *demi-plié* prior to *sauté*, and; 5) *demi-plié* prior to *sissone fermée de côté*. The symbol ø represents a long period of interval for the selected participant between experimental conditions. Horizontal lines in burgundy tones represent the frequency bands alpha (8-13 Hz), low-beta (13-18 Hz), and high-beta (18-30 Hz).

8.3.2 Comparisons amongst the experimental conditions with the simple demi-plié

In the present study, the *demi-plié* prior to subsequent movements was analyzed and compared to the execution of the simple *demi-plié*. Metrics such as integral, Q50, and IQR were utilized in analyzing data from the selected frequency bands, along with their relative measures. Significant differences ($p<0.05$) were found for the *demi-plié* prior to *sissonne fermée de côté*, *demi-plié* prior to *sauté*, and *demi-plié* prior to *pirouette en dehors,* when those movements were compared to the simple *demi-plié.*

In terms of lateralization, which refers to the dominance of one hemisphere of the brain in specific functions, in the context of motor functions, we could expect to see lateralized activity in the brain areas controlling the opposite side of the body that is engaged in a task. In our case, the *demi-plié* is visually a symmetrical movement; however, according to the statistical analysis (Tables 1, 2 and 3), significant differences were found for the EEG channels representing the right hemisphere of the brain (F4, C2, and C4), therefore controlling the left side of the body.

8.3.2.1 Demi-plié **prior to** *sissonne fermée de côté* **and** *demi-plié*

The comparison between the performance of the *demi-plié* prior to *sissonne fermée de côté* with the simple *demi-plié* showed significant differences in all channels regarding all the frequency bands and their relatives, except for C1 that showed differences only in the frequency bands relative measures (Table 1). The frequency bands relative measures showed differences only in the integral metrics for all channels, except for F4, which also showed differences in the IQR metric (Table 1). This pair of comparisons also showed significant differences in the inverted order, which means when the simple *demi-plié* showed higher power than the *demi-plié* prior to *sissonne fermée de côté*. Those differences were observed in the Q50 metric, which showed differences in the alpha frequency band for Cz and C4; in the low-beta for Cz, C2, C4, Fz, and F4, and; the high-beta for F3, Fz, and F4. The IQR metric showed differences in the alpha frequency band for C2, C4, and F4, and; in the low-beta for C3, C2, F3, and F4 (Table 1).

Table 1: Significant differences ($p<0.05$) with Bonferroni *post-hoc* comparisons of significant values for all the frequency bands analyzed along with their relative differences (r-), and for the metrics: integral (orange); Q50 (median) (purple); and IQR (interquartile range) (blue) between pairs of ***demi-plié* in preparation for *sissonne fermée de côté*** and simple *demi-plié*. The symbol (§) indicates when the *demi-plié* showed higher power than the *demi-plié* prior to *sissonne fermée de côté*.

Channels	alpha	low-beta	high-beta	r-alpha	r-low-beta	r-high-beta
C3		0.030 §		0.001	0.000	0.000
C1				0.003	0.001	0.001
Cz	0.027 §	0.044 §		0.023	0.001	0.000
C2	0.030 §	0.045 §		0.000	0.000	0.000
		0.019 §				
C4	0.044 §	0.017 §		0.007	0.001	0.000
	0.019 §					
F3		0.012 §	0.008 §	0.005	0.001	0.000
Fz		0.009 §	0.001 §	0.001	0.004	0.000
F4	0.046	0.002 §	0.012 §	0.001	0.001	0.000
		0.005 §				0.007

8.3.2.2 Demi-plié prior to *sauté* and *demi-plié*

The comparison between the performance of the *demi-plié* prior to *sauté* with the simple *demi-plié* showed significant differences in all channels regarding all the frequency bands relative measures to the integral metric (Table 2). The high-beta frequency band showed differences in C1, C2, and Fz; low-beta showed differences in C2, and; alpha showed differences in C2 and F4, all regarding the integral metric (Table 2). This pair of comparisons also showed significant differences in the inverted order, which means when the simple *demi-plié* showed higher power than the *demi-plié* prior to *sauté*. This difference was observed in the Q50 metric for channel Cz (Table 2).

Table 2: Significant differences ($p<0.05$) with Bonferroni *post-hoc* comparisons of significant values for all the frequency bands analyzed along with their relative differences (r-), and for the metrics: integral (orange); Q50 (median) (purple); and IQR (interquartile range) (blue) between pairs of ***demi-plié* in preparation for *sauté*** and simple *demi-plié*. The symbol (§) indicates when the *demi-plié* showed higher power than the *demi-plié* prior to *sauté*.

Channels	alpha	low-beta	high-beta	r-alpha	r-low-beta	r-high-beta
C3				0.000	0.000	0.000
C1			0.044	0.000	0.000	0.000
Cz	0.016 §			0.000	0.000	0.000
C2	0.044	0.017	0.003	0.000	0.000	0.003
C4				0.000	0.000	0.000
F3				0.000	0.000	0.000
Fz			0.007	0.000	0.000	0.000
F4	0.007			0.000	0.000	0.000

8.3.2.3 Demi-plié prior to *pirouette en dehors* and *demi-plié*

The comparison between the performance of the *demi-plié* prior to *pirouette en dehors* with the simple *demi-plié* showed significant differences in all channels regarding all the frequency bands relative measures to the integral metric (Table 3). Differences were also found in Fz regarding all frequency bands, and in F4 regarding high-beta (Table 3).

This pair of comparisons also showed significant difference in the inverted order, which means when the simple *demi-plié* showed higher power than the *demi-plié* prior to *pirouette en dehors*. This difference was observed in the Q50 metric for channel F4 (Table 3).

Table 3: Significant differences ($p<0.05$) with Bonferroni *post-hoc* comparisons of significant values for all the frequency bands analyzed along with their relative differences (r-), and for the metrics: integral (orange); Q50 (median) (purple); and IQR (interquartile range) (blue) between pairs of ***demi-plié* in preparation for *pirouette en***

dehors and simple *demi-plié*. The symbol (§) indicates when the *demi-plié* showed higher power than the *demi-plié* prior to *pirouette en dehors*.

Channels	alpha	low-beta	high-beta	r-alpha	r-low-beta	r-high-beta
C3				0.011	0.019	0.011
C1						0.005
Cz				0.013	0.003	0.012
C2				0.002		
C4				0.002	0.001	0.005
F3				0.016	0.017	0.012
Fz	0.047	0.019	0.019	0.017	0.004	0.005
F4			0.030 §	0.017	0.011	0.007

To better illustrate the significant differences found for the *demi-pliés* prior to *sissonne fermée de côté*, *sauté*, and *pirouette en dehors*, when compared to the execution of the simple *demi-plié*, Figure 3 displays a comprehensive diagram of the brain activity related to M1, PMC, and SMA correspondent to the performance of those movements, as well as the frequency bands and their relative measures that are active during such performances.

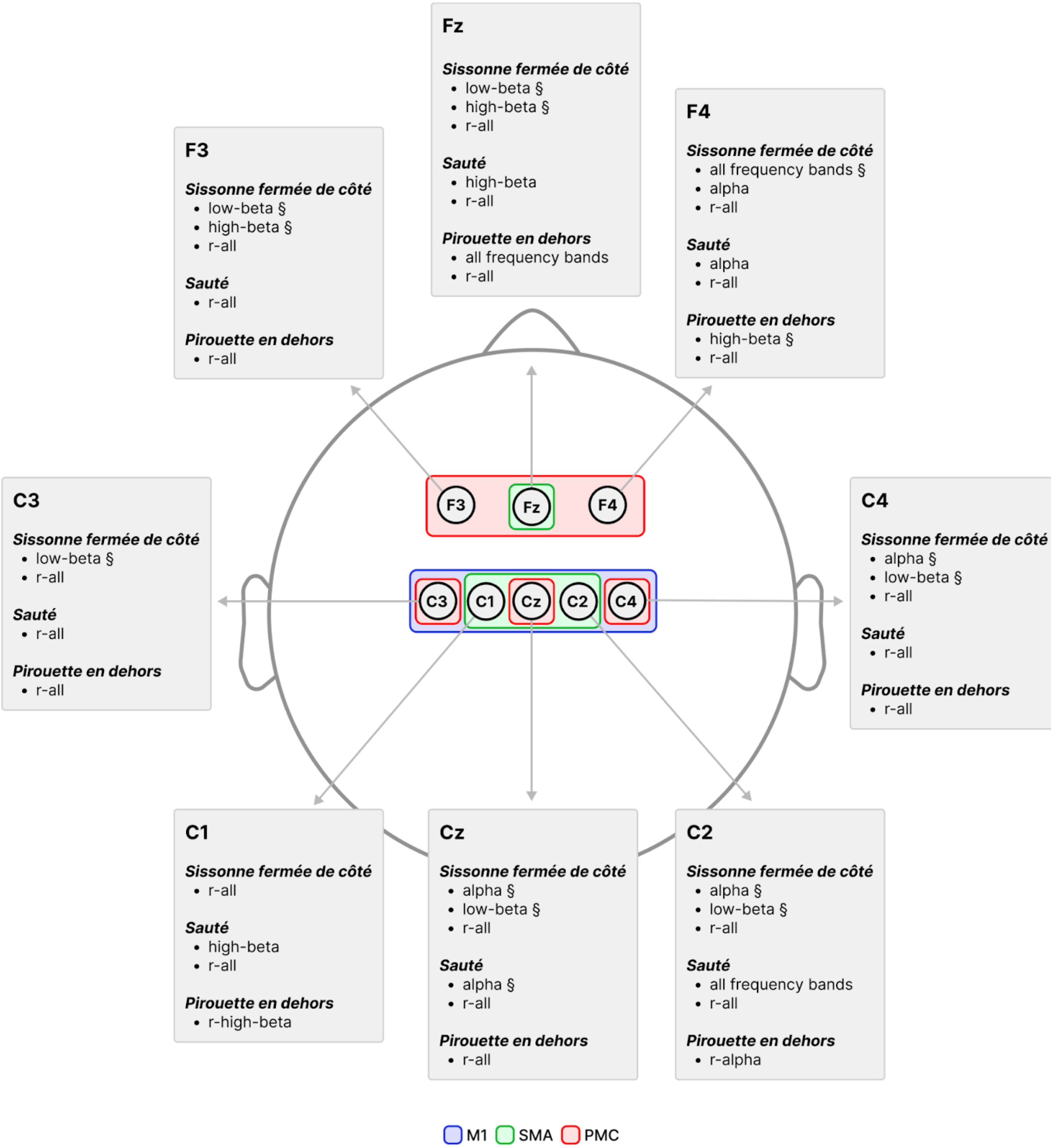

Figure 3: Diagram of each EEG channel displaying each frequency band and their relative measures that showed significant differences ($p<0.05$) for the *demi-plié* in preparation for *sissonne fermée de côté*, *sauté*, and *pirouette en dehors* when compared to the execution of the simple *demi-plié*. "All frequency bands" represent significant differences regarding alpha, low-beta, and high-beta, and "r-all" represents all relative measures of alpha, low-beta, and high-beta frequency bands. The symbol (§) indicates when the *demi-plié* showed higher power than the *demi-plié* prior to other movements. M1 - primary motor area, SMA - supplementary motor area, and PMC - premotor cortex area.

8.4 DISCUSSION

The aim of this study was to analyze the brain cortical activation during the performance of the *demi-plié* movement of classical ballet in five different experimental conditions, which were characterized by the *demi-plié* itself; *demi-plié* in preparation for *relevé*; *demi-plié* in preparation for sauté; *demi-plié* in preparation for *sissone fermée de côté*, and; *demi-plié* in preparation for *pirouette en dehors*. We hypothesized that different brain cortical activation would be shown in the EEG analysis depending on the *demi-plié* end-goal, in regards to the frequency bands alpha, low-beta, and high-beta. Indeed, our findings have shown distinct brain cortical activity in the various EEG channels and for the different frequency bands analyzed, which can lead to the interpretation that the brain cortical activity during the performance of the *demi-plié* varies depending on its end-goal.

The statistical analysis showed that the *demi-plié* movement that precedes both jumps (i.e., *sauté* and *sissone fermée de côté*) showed the highest differences ($p<0.01$) in all statistical metrics, followed by the *demi-plié* that precedes the *pirouette en dehors* when compared to the simple *demi plié* performance. The *demi-plié* prior to *relevé* did not show significant differences, and a possible explanation is due to this movement being more similar to the simple *demi-plié* in terms of duration, physical impact, and plyometric forces, in comparison to the performance of the *demi-plié* that preceded both jumps and the *pirouette en dehors*.

The wavelet spectrograms displayed different patterns for the different experimental conditions, showing that different cortical areas such as the M1, PMC, and SMA seem to be more or less active depending on the *demi-plié* end-goal, and this dependency seems to be related to the level of complexity of the ballet movement prepared by the *demi-plié.* For instance, the alpha band is known to be indicative of a relaxed, yet alert state and is often prominent when the individual is in a state of wakeful rest with their eyes closed. The pronounced alpha rhythm showing higher powers in the metric integral for the *demi-plié* that precedes the *sauté* and the *pirouette en dehors* suggests that during this movement, the participant was likely performing the task in a more relaxed state when compared to the other *demi-pliés*. Enhanced alpha and low-beta activity may indicate active sensorimotor integration in M1, where the brain is processing sensory information relevant to the movement, such as position, speed, and force, and adjusting motor outputs accordingly. The presence of low-beta rhythm across the various *demi-pliés* suggests a fluctuation in attention and cognitive demand required for the performance of these movements, which is typical during tasks that involve complex motor execution and coordination. Lastly, the higher power in the high-beta range for the *demi-plié* that precedes both jumps and also the one that precedes the *pirouette* can be interpreted as periods of increased neural processing and active engagement, potentially reflecting the complex motor and cognitive integration needed for the precise execution of the ballet sequences.

Our findings showed that M1, PMC and SMA were highly active in the *demi-plié* prior to *sissonne fermée de côté*, possibly because the *sissonne fermée de côté* is a jump-land ballet movement with lateral body displacement, starting with a *demi-plié* for impulse to a vertical jump and immediately displacement of the body laterally, as the ballet dancer simultaneously extends both legs in the air as scissors, having the leading leg raised at approximately 22.5 degrees away from the midline of the body, and the trailing leg rising by pushing off the ground [29]. It makes sense that the *demi-plié* prior to *sissonne fermée de côté* showed the main significant differences alongside the *demi-plié* prior to *sauté*. The leading leg plays a crucial role in initiating the movement by plantarflexing the ankle and extending the knee. It also takes on the responsibility of absorbing impact force upon landing. On the other hand, the trailing leg has the task of stabilizing the body before the leading leg contacts the ground. Once the leading leg touches the ground, the trailing leg swiftly moves closer to it. In regards to the PMC, the *demi-plié* prior to *sissonne fermée de côté* possibly required both hemispheres to be active, as it is a complex movement, requiring significant motor control, cognitive engagement, and potentially involving both hemispheres and midline structures, integrating motor execution with higher-order cognitive processes.

The SMA activity was more expressive in the *demi-plié* prior to *sauté*, possibly due to the symmetry nature of this movement, as the electrodes corresponding to SMA are Fz and Cz, covering the midline of the brain. Even though C1 and C2 can also capture some activity in SMA, possibly showing some lateralization, there were not significant findings for them. The SMA is essential for the initiation and temporal organization of movements. This could involve strategic planning, the anticipation of movement outcomes, or adjustments based on ongoing feedback, with the importance of both motor and cognitive domains in executing complex or precisely timed movements.

Lateralization plays an important role in our findings. According to the statistical analysis (Tables 1, 2 and 3), there are more significant differences for the electrodes positioned in the right hemisphere of the brain than to the ones positioned in the left side, which may suggest that activity on the right hemisphere presents more differences amongst the movements performed than the left hemisphere. A possible explanation for those findings lies in the fact that the *demi-plié* is a symmetrical movement, where both legs supposedly behave in the same way. Perhaps, the right hemisphere has to increase control of the left leg in order to decrease differences in the non-dominant side during the *demi-plié* performance, since all of the participants were right-side dominant. Additionally, right-side dominant ballet dancers often prefer to perform the *sissone fermée de côté* displacing the body in space towards the left side, so that the right leg can reach higher amplitudes. This movement requires that the left side of the body commands its own orientation, increasing the demand for the right brain hemisphere to plan and execute the task. In regards to the performance of a *pirouette en dehors*, right-side dominant ballet dancers often prefer to perform the *pirouette* revolution clockwise, using the left leg to provide balance and behave as a fluid pivot. Once again, the right brain hemisphere would then be more active in order to command the left leg of the ballet dancer. Nonetheless, future research should address a left-side dominant sample of ballet dancers in order to compare with the current findings.

Previous research from Golomer and colleagues (2010) [30] investigated unipedal balance in skilled ballet dancers, suggesting that in dynamic equilibrium conditions, such as performing a revolution in a *pirouette*, the unipedal upright posture could highlight the role of the lateralized somatosensory and motor systems in central regulation due to the demand for visual cue. This central dominance would result in a functional postural dominance that influences hemispheric asymmetries in the sensorimotor control. Indeed, our findings showed high activation in the right hemisphere during the performance of the *demi-plié* prior to *pirouette en dehors* in comparison to the simple *demi-plié*.According to Ushiyama and colleagues (1985), ballet dancers develop adaptation of the strategy used by the central nervous system to perform a particular muscular contraction after years of specialized practice, suggesting that anticipatory adjustments will occur depending on the subsequent motor action involved in the movement planning. Our findings corroborate theirs, even though our sample size varied in expertise levels of the ballet dancers. Nonetheless, our findings suggest that the *demi-plié* movement execution may present differences at the cortical control depending on its end-goal, despite the expertise level.

The implications of our study could significantly impact the optimization of training and rehabilitation methods in ballet. Ballet instructors, specifically, might find these insights extremely valuable for improving the efficiency of training sessions and rehearsals. By integrating our findings, they can better manage muscle fatigue and reduce the risk of injuries. This proactive training approach has the potential to revolutionize traditional ballet teaching methods, fostering a more sustainable practice that emphasizes the health and longevity of dancers.

To the best of our knowledge, this is the first study analyzing brain cortical activity during the performance of a ballet movement. Despite some limitations such as the small number of

EEG channels, as well as the diverse sample size of different levels of expertise and the imbalance of sexes, it was possible to confirm our hypothesis that the *demi-plié* movement of classical ballet presents different patterns of brain cortical activation in the M1, PMC, and SMA, depending on its end-goal. The present study contributes to a baseline of knowledge that is being created in order to understand the fascinating beauty and aesthetics seen in classical ballet, a field of highly performing individuals.

8.5 CONCLUSIONS

Regarding the analysis of the sensorimotor cortex activity in the frequency bands alpha, low-beta, and high-beta, the *demi-plié* movement of classical ballet presents different brain cortical activation patterns depending on its end-goal.

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CHAPTER 9:

General Discussion & Conclusions

9.1 GENERAL DISCUSSION

The aim of the present dissertation was to analyze the performance of the *demi-plié* in its different roles in classical ballet. Four studies have been conducted in order to prove our hypothesis that the same apparent *demi-plié* performed by a classical dancer, but with different end-goals, will differ at the coordination level, muscular activation pattern, and brain cortical activation.

Our findings have shown that, indeed, regarding the *demi-plié* performance with different end goals, the *demi-plié* that precedes any subsequent technique presents dissimilarities in its trajectory in the terms of the vertical movement of the pelvic complex; different coordination patterns in terms of the knees joint angles and their angular velocity; distinct muscular activation patterns, and; different brain cortical activation.

The concept of global internal models for motor control is a theoretical construct in neuroscience and psychology that describes how the brain predicts and controls body movements (Kawato, 1999). In other words, global internal models are complex neural processes that enable the brain to predict, simulate, and adjust motor actions, ensuring effective interaction with the physical world. These models are fundamental in understanding how we learn and execute movements, ranging from simple tasks like reaching for an object to complex activities like playing a musical instrument, engaging in sports, or in our case, performing a ballet movement. According to Flanagan et al. 1999, global internal models adapt to different sensorimotor contexts, as the CNS must learn the properties of tools and environments whenever they are altered. It seems that if the CNS knows how to command the execution of a *demi-plié*, when its end-goal changes, the process of execution may be facilitated by combining multiple ways to perform it in anticipation of the next motor action. Even though each experimental condition has shown its unique coordination pattern, there were similarities amongst those patterns, possibly related to the level of complexity of the subsequent ballet movement. For instance, the simple *demi-plié* is an isolated movement that has its starting and ending position within the lower limb, pelvis and trunk. However, when it is coupled to subsequent ballet movements, the ascending phase is often accelerated to fuse into the next motor action. The level of complexity of the subsequent movement will interfere in the anticipatory adjustments required during the *demi-plié* performance.

Our findings are consistent in showing differences amongst the types of the *demi-plié* when it is in preparation for jumps (i.e., *sauté* and *sissone fermée de côté*) and in preparation for turns (i.e., *pirouette en dehors*). However, there were similarities in the coordination patterns amongst the jumps, as well as between the simple *demi-plié* and the one in preparation for a *relevé*. The similarities amongst these groups of motor actions is probably due to the similar level of complexity. Presumably, the CNS creates similar strategies to perform jumps, taking into consideration the forces applied to take off the ground, controlling directions of the jump, and working on perceptual and motor adjustments for absorbing impact upon landing. Those similarities amongst some groups of motor actions also create the distinctions noticed in our experiments, since one of the jumps was vertical (*sauté*), and the other was a lateral body displacement (*sissone fermée de côté*). Likewise, the *relevé* is a movement that demands heel rise and does not present impact during its execution or finishing. Not surprisingly, the *demi-plié* prior to *relevé* presented similarities in its coordination patterns with the simple *demi-plié*.

The *demi-plié* prior to *pirouette en dehors* has shown its unique coordination pattern in the kinematic analysis, and it showed to be one of the most complex movements in terms of brain organization as well, alongside with the *demi-plié* prior to both jumps when pairs of movements were compared to the simple *demi-plié*. Perhaps the experiment with the *pirouette en dehors* should be redone with the *demi-plié* in the fourth position of feet in classical ballet, typically used to prepare for the revolutions. In our experimental design, we standardized the first position of feet for all experimental conditions.

Findings from the EEG analysis also showed distinct patterns in brain activity for the *demi-plié* that precedes *sauté, sissone fermée de côté,* and *pirouette en dehors* in comparison to the simple *demi-plié*, with varying levels of alpha, low-beta, and high-beta waves. This is indicative of different states of relaxation, attention, and cognitive demand. The wavelet spectrograms displayed different patterns for the different experimental conditions, showing that different cortical areas such as the M1, PMC, and SMA seem to be more or less active depending on the *demi-plié* end-goal, and this dependency seems to be related to the level of complexity of the ballet movement prepared by the *demi-plié.* The study also revealed a lateralization effect, with the right hemisphere of the brain showing more activity. One potential reason for these observations could be attributed to the symmetrical nature of the *demi-plié*, which typically involves both legs moving in a coordinated manner. Perhaps, the right hemisphere has to increase control of the left leg in order to decrease differences in the non-dominant side during the *demi-plié* performance, since most of the participants were right-side dominant. Furthermore, ballet dancers who predominantly use their right side tend to favor executing the *sissone fermée de côté* in a manner that involves shifting the body to the left, allowing the right leg to achieve greater extension. This action necessitates the left side of the body to direct the body's positioning, potentially requiring increased involvement from the right hemisphere of the brain for planning, execution, and oversight. Similarly, when performing a *pirouette en dehors*, right-dominant ballet dancers usually opt for a clockwise rotation, relying on the left leg for stability and smooth turning. This again suggests a heightened role for the right hemisphere in managing the left leg movement. Future studies should consider including dancers who are left side dominant to provide a comparative analysis with the current findings.

Despite our primary interest in understanding the coordination patterns involved in the *demi-plié* movement and its role in the preparation for more complex subsequent motor actions, our research took into consideration the lack of literature about using some types of sensing technology to acquire data. For instance, our systematic review has shown that two or more sensing technologies increase data reliability, as well as to this date, no one had studied the brain activity aspects of a ballet movement during its performance. As a result, we designed our methodology for data capturing, choosing a robust scenario where different technologies could work in synchronicity, combining motion capture, EMG, and EEG. Unfortunately, limitations occurred, and we did not have access to an EEG device with more channels, being limited to the analysis of the sensorimotor cortex only. However, the pioneer work using the EEG technology during a ballet motor action, as well as novel approaches in data analysis, such as the DTW and ED to measure the hip vertical trajectory of the *demi-plié*, definitely increased the baseline of knowledge in ballet research, paving the pathway for future studies.

The *demi-plié* movement is one of the first movements that a ballet dancer learns, and it is also present in every ballet class, in the barre routine; right in the beginning of the class, as well as in the center; as the first exercise to do after finishing the barre routine. The implications of our findings go beyond the scientific understanding of motor performance and behavior, providing ballet teachers and maestros with solid evidence that if the *demi-plié* behaves in distinct ways depending on its end-goal, perhaps, routines of the *demi-plié* should be implemented taking into consideration the next motor action it precedes. In this way, it might be possible to control the number of repetitions, creativity in designing ballet routines, and order of rehearsals to avoid physical overload and possibly prevent injuries. There is a vast literature in the ballet field, including systematic reviews, pointing to the risk factors for musculoskeletal disorders and lower limb injuries that can be prevented through modified training in order to make it safer (Benoit-Piau et al. 2022, 2023; Kenny et al. 2016; L Biernacki et al. 2021).

9.2 CONCLUSIONS

The *demi-plié* movement of classical ballet presents different coordination patterns in terms of interlimb coordination, hip vertical movement trajectory, muscular activation patterns, and brain cortical activation depending on its end-goal.

Those differences manifest depending on the complexity of the subsequent motor action. Complex ballet movements such as jumps (i.e., *sauté* and *sissone fermée de côté*) and turns (i.e., *pirouette en dehors*) seem to present distinct coordination patterns of the *demi-plié* that precedes these movements, when compared to the performance of the simple *demi-plié*. Also, the *relevé*, with lower levels of complexity, indeed showed distinct coordination patterns when compared to both *sauté* and *sissone fermée de côté*, as well as to the *pirouette en dehors*. Muscular activation has shown distinct patterns for each *demi-plié* as well, suggesting that muscle recruitment works in anticipation of the next motor action. Brain cortical activity also showed differences related to the level of complexity of the subsequent ballet. We have confirmed our hypotheses that the *demi-plié* movement would present distinct coordination patterns and brain cortical activations depending on its role in classical ballet.

APPENDIX A

CONSENTIMENTO INFORMADO LIVRE E ESCLARECIDO PARA INVESTIGAÇÃO CIENTÍFICA COM SERES HUMANOS

Título do projeto: Coordination patterns and brain activation during the *demi-plié* movement in its different roles in classical ballet

Pessoa responsável pelo projeto: Virgínia Helena Quadrado

Instituição de acolhimento: Faculdade de Motricidade Humana - Universidade de Lisboa

Este documento, designado **Consentimento, Informado, Livre e Esclarecido**, contém informação importante em relação ao estudo para o qual foi abordado/a, bem como o que esperar se decidir participar no mesmo. Leia atentamente toda a informação aqui contida. Deve sentir-se inteiramente livre para colocar qualquer questão, assim como para discutir com terceiros (amigos, familiares) a decisão da sua participação neste estudo.

Informação geral

A vossa participação nesta pesquisa inclui a execução do movimento plié em 5 (cinco) condições experimentais, sendo:

1) Execução do movimento *demi-plié*
2) Execução do movimento *demi-plié* como preparação para relevé (elevação dos calcanhares)
3) Execução do movimento *demi-plié* como preparação para sauté (salto vertical)
4) Execução do movimento *demi-plié* como preparação para pirouette en dehors (volta no sentido horário realizado em uma perna)
5) Execução do movimento *demi-plié* como preparação para sissonne fermée (salto com deslocamento lateral)

Qual a duração esperada da minha participação?

A duração do experimento será de aproximadamente 60 minutos.

Quais os procedimentos do estudo em que vou participar?

Cada condição experimental será repetida 5 vezes para que os investigadores possam registar o movimento.

Cada participante terá de vestir um fato com marcadores refletores e eletrodos para medir atividade muscular que serão acoplados em ambas as pernas. Cada participante usará uma coroa de eletrodos na cabeça para medição de atividade cerebral.

A minha participação é voluntária?

A sua participação é voluntária e pode recusar-se a participar. Caso decida participar neste estudo é importante ter conhecimento que pode desistir a qualquer momento, sem qualquer tipo de consequência para si. No caso de decidir abandonar o estudo, a sua relação com a Faculdade de Motricidade Humana (FMH) não será afetada. Se for o caso, o seu estatuto enquanto estudante ou funcionário da FMH será mantido e não sofrerá nenhuma consequência da sua não-participação ou desistência.

Quais os possíveis benefícios da minha participação?

Os dados recolhidos por meio de sua participação serão analisados juntamente com os dados dos demais participantes, com a finalidade de compreendermos os padrões de coordenação e atividades musculares envolvidas nos diferentes tipos de *demi-plié* no ballet clássico. Além disso, por meio da análise de eletroencefalografia, poderemos mapear as áreas cerebrais envolvidas no processo de execução do movimento *demi-plié*. Esta é uma pesquisa pioneira na área da dança e controle motor, dando-nos respaldo para contribuir cientificamente por meio de publicação dos resultados

Quais os possíveis riscos da minha participação?

Possíveis riscos envolvidos são quedas no momento da pirueta e estiramento muscular no momento do salto. Cada participante terá 10 minutos de familiarização com a tarefa e aquecimento muscular para minimização dos riscos envolvidos.

Quem assume a responsabilidade, no caso de um evento negativo?

Investigador principal: Virginia Helena Quadrado

Há cobertura por uma companhia de seguros?

Não há cobertura por companhia de seguros.

Quem deve ser contactado em caso de urgência?

Investigador principal: Virgínia Helena Quadrado (virginiahelena@gmail.com)

Como é assegurada a confidencialidade dos dados?

Todos os dados recolhidos serão armazenados e codificados de forma a que seja mantida a confidencialidade dos dados.

O que acontecerá aos dados quando a investigação terminar?

Todos os dados recolhidos serão armazenados no ficheiro pertinente à investigação para possível comparação futura entre movimentos de ballet clássico.

Como irão os resultados do estudo ser divulgados e com que finalidades?

Os resultados serão divulgados por meio de artigos científicos e publicações em conferências pertinentes à área de controle motor e dança.

Em caso de dúvidas, quem devo contactar?

Para qualquer questão relacionada com a sua participação neste estudo, por favor, contactar o investigador principal através do e-mail: virginiahelena@gmail.com

Assinatura do Consentimento Informado, Livre e Esclarecido

Li (ou alguém leu para mim) o presente documento e estou consciente do que esperar quanto à minha participação no estudo Coordination patterns and brain activation during the *demi-plié* movement in its different roles in classical ballet. Tive a oportunidade de colocar todas as questões e as respostas esclareceram todas as minhas dúvidas. Assim, aceito voluntariamente participar neste estudo. Foi-me dada uma cópia deste documento.

Nome do participante **Assinatura do participante**

Data

Nome do representante legal do participante
(se aplicável)

Grau de relação com o participant

Investigador/Equipa de Investigação

Os aspetos mais importantes deste estudo foram explicados ao participante ou ao seu representante, antes de solicitar a sua assinatura. Uma cópia deste documento ser-lhe-á fornecida.

Nome da pessoa que obtém o consentimento **Assinatura da pessoa que obtém o consentimento**

Data

APPENDIX B

Link of the questionnaire that all participants answered in order to collect information about demographics, experience in classical ballet, dominance limb, and presence or absence of injury.

Access the questionnaire here.

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