

What is the influence of a 6-weeks, specific physical preparation protocol on landing impacts in Artistic Gymnastics elements?

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Resumo

A receção de um ginasta é um movimento altamente complexo, cujo sucesso depende de vários fatores. Este estudo investiga estratégias para melhorar as técnicas de receção na ginástica, avaliando especificamente o impacto de um protocolo de preparação física específica de seis semanas nas mesmas. O objetivo é otimizar o desempenho dos ginastas através da análise de aspetos biomecânicos reportados ao longo do tempo na literatura. O objetivo principal é avaliar o impacto do protocolo de preparação física específica em atletas de alto rendimento de Ginástica Artística Feminina e Masculina. Os objetivos específicos incluem a análise da atividade eletromiográfica, das forças de reação ao solo e da dinamometria isocinética relacionadas com as receções, bem como a sua influência na estabilidade, no controlo motor e no desempenho global dos atletas. Este estudo baseia-se na hipótese de que a preparação física específica pode conduzir a melhorias mensuráveis no desempenho das receções dos ginastas. Espera-se que a intervenção resulte num aumento da ativação muscular, numa redução das forças de reação ao solo, em ganhos de força e numa maior coordenação geral durante as receções. Os resultados demonstraram que o programa elaborado pode melhorar o desempenho das receções, promovendo uma melhor ativação muscular e reduzindo as forças de reação ao solo. Apesar das limitações associadas ao tamanho reduzido da amostra, ao combinar uma revisão sistemática com um estudo experimental, esta investigação culmina em recomendações baseadas em evidências para melhorar a segurança e o desempenho nas receções do salto extensão, meia pirueta, uma pirueta, mortal à frente, mortal atrás e salto de contramovimento, contribuindo assim de forma relevante para o conhecimento existente e oferecendo informações práticas para treinadores e atletas da modalidade. Nomeadamente a evidência de que o foco na força, mobilidade e coordenação tornam as técnicas de receções dos ginastas bastante mais corretas e seguras.

PALAVRAS-CHAVE: GINÁSTICA ARTÍSTICA, RECEÇÕES, FORÇAS DE REAÇÃO DO SOLO, IMPACTOS, PREPARAÇÃO FÍSICA.

Abstract

The landing of a gymnast is a highly complex movement, whose success depends on several factors. This study investigates strategies to improve landing techniques in gymnastics, specifically assessing the impact of a six-week specific physical preparation protocol on them. The objective is to optimize gymnasts' performance by analyzing biomechanical aspects reported over time in the literature. The main goal is to evaluate the impact of the specific physical preparation protocol on elite athletes in Women's and Men's Artistic Gymnastics. The specific objectives include the analysis of electromyographic activity, ground reaction forces, and isokinetic dynamometry related to landings, as well as their influence on stability, motor control, and overall athlete performance. This study is based on the hypothesis that specific physical preparation can lead to measurable improvements in gymnasts' landing performance. The intervention is expected to result in increased muscle activation, reduced ground reaction forces, strength gains, and greater overall coordination during landings.

The results demonstrated that the developed program can improve landing performance by promoting better muscle activation and reducing ground reaction forces. Despite the limitations associated with the small sample size, by combining a systematic review with an experimental study, this research culminates in evidence-based recommendations to enhance safety and performance in landings of the stretched jump, half turn, full turn, front somersault, back somersault, and countermovement jump. Thus, it makes a relevant contribution to existing knowledge and provides practical insights for coaches and athletes in the sport. Specifically, the evidence highlights that focusing on strength, mobility, and coordination leads to significantly more accurate and safer landing techniques of the gymnasts'.

KEYWORDS: ARTISTIC GYMNASTICS, LANDINGS, GROUND REACTION FORCES, IMPACTS, PHYSICAL PREPARATION.

List of abbreviations and acronyms

ACL – Anterior Cruciate Ligament
AVG – Average
BB – Balance Beam
BS – Back Somersault
CMJ - Counter Movement Jump
CV – Coefficient of variation
EMG – Electromyography
EJ – Extension Jump
F – Floor
FIG – International Federation of Gymnastics
FS – Front Somersault
FT – Full turn
GL – Lateral Gastrocnemius
GM – Medial Gastrocnemius
GRF – Ground Reaction Forces
HB – Horizontal Bar
HT – Half Turn
IMUs – Inertial Measurement Units
MAG – Men Artistic Gymnastics
MVC – Maximal Voluntary Contraction
NMT – Neuromuscular Training
PB – Parallel Bars
PH – Pommel Horse
PL – Peroneus Longus
RFD – Rate of Force Development
ROM – Range of Motion
SR – Rings
TA – Tibialis Anterior
TPT – Time to Peak Torque
UB – Uneven Bars
VT – Vault

WAG – Women Artistic Gymnastics

1. Introduction

1.1 Relevance of the study

Artistic gymnastics is a complex and demanding sport that includes multiples athletic gestures in order to enable athletes to compete in various apparatus. With its competitive origins in 1894, artistic gymnastics was one of the original disciplines in the modern Olympic Games (Kaufmann et al., 2022) that evolved from 1896 onwards into what we recognize today as modern gymnastics. These specific gymnastics discipline separates into Women's Artistic Gymnastics (Mizutori et al., 2021) which the apparatus are: Vault (VT), Uneven Bars (UB), Balance Beam (BB) and Floor (F) and Men's Artistic Gymnastics that includes Floor, Vault, Pommel Horse (PH), Rings (SR), Parallel Bars (PB) and Horizontal Bar (HB).

The frequent changes of International Federation of Gymnastics (FIG) regulations turns Artistic Gymnastics into a "bicycle wheel" of constant change and evolution over time. These technical regulations outline the criteria for routine creation (Bandara & Chandana, 2022) and dictate the success of gymnastics competitions. Many times, gymnasts fail to fulfill all off these technical required standards resulting in lower scores during competitions. According to Campos (2010), coaches and gymnasts strategies, turn into a pursuit of elements with high difficulty to increase as much as possible their routines value.

As time passes by, high performance level gymnasts compete even more complex and difficult routines always aiming to achieve better results. Nonetheless, the performance of these routines depends significantly on different factors such as, motor knowledge, complexity of exercises coordination, and high demands of stability (Nassib et al., 2020). According to Readhead (2013), artistic gymnastics requires extraordinary levels of physical fitness, with an emphasis on strength to train and compete at the highest levels, with physical preparation

being the basis for all the training factors on which the pyramid of high performance is supported.

Injuries are one big problem related to the artistic gymnastics' world, since this is a sport with intense and physically challenging training. It is common in this sport that athletes start their practice at an early age leading to specialization and high training volumes since this young age (Daly et al., 2001). The frequency of difficult elements being performed, associated with the high amount of hours of practice turns gymnastics into a sport with a high risk of injury (Kolt & Kirkby, 1996). Regarding these factors, the high requirements of the sport can lead to an injury if the gymnast's body is pushed beyond the physiological and physical limits and does not respond with corrective treatment at the right time (Paunović et al., 2023). As the time off practice passes by, the level of skills increases, so does the load in the gymnastics limbs and simultaneously the frequency of acute injuries.

The high-impact landings and repetitive movements that gymnast's experiment can also lead to overuse injuries, such as stress fractures or tendinitis. Furthermore, collisions and falls are particularly common in gymnastics apparatus which exposes gymnasts to even bigger risk of injury (Kara et al., 2023). Since in the existing literature it is described that landings have a very low success rate in competition (Prassas & Gianikellis, 2002), coaches must be doated with strategies to implement in their practice to turn these landings into safer movements.

The existing literature till the moment makes refence to some successufy factors and abilities that must be the subject of a lot of interest and time in the training process, however there is no consensus about which one to dedicate more attention to, including landing techniques giving the coaches space to implement their one individual strategies. There is a major need for more research about successful aspects impacting talent development in gymnastics and future strategies to be implemented in practice by coaches that have a proper theoretical support base. It is essential that physical preparation with a focus on

developing strength and specific training for landings are worked rigorously and with the proper attention in practice.

Therefore, and taking as a starting point the lack of objective information about which is the most effective preparation for landings in gymnastics, we will seek with this analysis to get closer to a more direct answer to the question: What is the influence of a 6-weeks, specific physical preparation protocol on landing impacts in Artistic Gymnastics elements?

1.2 Formulation of the concept/idea of the work

Where did the problem, or question, that justifies this study related to the Gymnasts landings came from?

As the present work has a scientific nature, we admit that in order to answer the question that raises and guides it, it is also justified to answer the reasons behind this question. Where and how did the idea for the study come from?

During the degree, in the Gymnastics Methodology III course unit, a biomechanics research project on a topic of our choice was assigned. After exploring different areas of interest within gymnastics, we choose landings as the main focus of the research due to their presence at the end of all elements. As we began this research, we found a few studies that highlighted body posture (Devita & Skelly, 1992; Holden et al., 1997; Król et al., 2020; Sonvico et al., 2019; C. L. Wu et al., 2019), motor control (Chappell & Limpisvasti, 2008; Horita et al., 2002; Kochanowicz et al., 2019) and athlete's physical preparation (Daly et al., 2001; Hart et al., 2018; Williams et al., 2016) as key factors influencing the success of gymnasts' landings.

In addition to our growing interest in this area and my 15 years of practicing artistic gymnastics with daily involvement in the sport, I experienced various types of training that depended on different characteristics such as club structure, different coaches, and competitive levels. During this time, I was fortunate to have coaches and professionals around me who were concerned about my well-being and constantly asked how I was doing and if I felt any pain during exercises. Sharing opinions and feedback regarding the training process has always been a constant in my life as an athlete, and I firmly believe it fostered the curiosity and

critical thinking in me that now leads to daily questions about how to become a better coach. How can I ensure the athletes have safer landings? How can we reduce failed landings? How can we avoid landings to fail? These are questions that probably don't have a one-size-fits-all answer, but they make a coach a constantly evolving learner.

Combining these three roles: former artistic gymnast, master's student in high-performance training, and coach, came the ambition to study the landing movement of a gymnast more thoroughly using the university available biomechanical tools.

In almost all the research, "physical preparation" was cited as a crucial factor in gymnasts' landings, but its importance was often somewhat subjective.

Specific physical preparation in artistic gymnastics refers to the set of exercises and training designed to enhance physical capacities directly related to the demands of the sport. This preparation aims to optimize gymnasts' performance in their routines and minimize the risk of injuries. It involves several components, adjusted to meet the specific needs of the movements and skills required in artistic gymnastics such as muscular strength, coordination and balance, flexibility and specific technique and skills.

Specific physical preparation in artistic gymnastics is an important component of training, focusing on developing the physical capacities needed to perform complex movements with precision and safety. This type of preparation is personalized for each gymnast's level, considering their individual needs and performance goals.

As science dictates, the greatest base of evidence comes from experimentation and practice. Therefore, we conceived the idea of creating a six-week specific physical preparation protocol for the sport to observe effectively the improvement or lack of it in gymnasts' landings.

1.3 Objectives of the study

General objective:

- To assess the impact of a six-week, specific landing physical preparation protocol in high-performance athletes from Women Artistic Gymnastics and Men Artistic Gymnastics.

Specific objectives:

- Analyze the influence of a specific landing training protocol on the electromyographic (EMG) activity of the muscles, ground reaction forces of the elements and exercises using isokinetic dynamometry.
- Identify and synthesize the available scientific literature addressing the landing ability on different apparatus from artistic gymnastics based on different methods of evaluation.
- Analyze changes in landing biomechanics following the implementation of the protocol.
- Identify if there are any changes in landing stability, motor control, and overall performance as a result of the intervention.
- Provide evidence-based recommendations for coaches and athletes aiming to enhance landing safety and performance in 2Artistic Gymnastics.

1.4 Hypotheses

By implementing the specific physical preparation program, we aim to collect relevant results regarding landings in common elements of both men's and women's artistic gymnastics. We expect to observe significant improvements in the performance of floor element landings after the 6-week intervention protocol, reflected in both techniques and effectiveness of landings.

For this same reason, the hypotheses of this work will be as follows:

1. The intervention program will result in increased lower limb muscle activation during both pre-activation and landing phases, as measured by EMG.
2. Ground reaction forces during landings, measured using force platforms, will show a statistically significant decrease after the intervention, indicating improved force absorption and transmission capabilities.
3. Isokinetic testing will reveal enhanced force production capacity in the gymnast's post-intervention, particularly in muscles involved in floor landings.
4. Gymnasts' overall coordination, specifically in controlling movements during landings, will be improved.

These hypotheses will guide the evaluation of the intervention's effectiveness by comparing pre and post-protocol assessments to ascertain statistically significant improvements in the gymnasts' landings performance and physiological parameters.

1.5 Work structure

This exploratory work will be presented in the form of a dissertation following what is commonly referred to as the mixed model. At the beginning of this document, following the cover and the cataloging sheet, will be the acknowledgments, the index containing all parts, subparts, chapters, and subchapters, as well as all tables and figures included in the document. Following this, we will have the abstract and the list of abbreviations used throughout the text.

Next, this document contains an introduction where it was described the state of knowledge in the area of interest, define a set of unresolved problems that support the formulation of the work's purposes, present the objectives and hypotheses of the study, and provide a brief outline of the structure of the work. After the introduction, we conduct a literature review where it was described what artistic gymnastics entails, the role of landings in this sport, the existing evidence in the literature about landing training in artistic gymnastics, explain what a

specific physical preparation training protocol involves, and the relevance of these concepts to the conducted study.

Subsequently, this work is divided into two parts: the first is a systematic review article on the biomechanical aspects of landings in artistic gymnastics titled "THE IMPACT OF LANDINGS AND GROUND REACTION FORCES IN ARTISTIC GYMNASTIC" ' which has already been published in Volume 17 No. 1. (2025) in the Science of Gymnastics Journal, a journal with an impact factor of 0.6.

The second part consists in the second article, which is an experimental study about biomechanics realized at Porto Biomechanics Laboratory (Labiomep) and served as the main research method for this work. This paper is titled "WHAT IS THE INFLUENCE OF SPECIFIC PHYSICAL PREPARATION TRAINING IN THE IMPACT OF LANDINGS IN ARTISTIC GYMNASTICS ELEMENTS?".

We chose to organize the work in this way in order to first, gather all existing knowledge in the literature on the topic of landings in gymnastics, identify its gaps, flaws, or questions we wanted to explore, and subsequently test in practice a key factor we found to be crucial for executing a good landing according to the literature: specific physical preparation. The bibliography is not divided by sections indexed to each article, there is a general bibliography related to the overall master's dissertation. At the end of the document, there is a general discussion that considers the new state of knowledge in the field after the particular contributions of each article, integrating and weighing their combined influences in the conclusion chapter of the work and also the attachments section.

2. Literature review

2.1 Overview of the sport

Artistic gymnastics is a sport with a rich history dating back to ancient civilizations, where physical training and acrobatic exercises were integral parts of military and cultural activities (Kilijanek & Sanchez, 2020). Early forms of gymnastics were practiced in ancient Greece, where physical fitness was deeply valued in society. This early form of physical training, known as "gymnastike," included various disciplines such as running, jumping, and wrestling, which were incorporated into the ancient Olympic Games (Kilijanek & Sanchez, 2020).

Gymnastics as an organized sport debuted on the international stage during the first modern Olympic Games in 1896, in Athens. Only men competed in these early Olympic gymnastics' competitions, which included events such as rope climbing and horizontal bar exercises. In 1928 Olympic Games in Amsterdam women's artistic gymnastics was introduced, though the events for women were limited to team competitions initially (Green & Hardman, 2005).

The sport continued to evolve throughout the 20th century, with the addition of new apparatuses and more standardized rules for judging performances. The development of artistic gymnastics was further shaped by the influence of the Soviet Union in the mid-20th century (Krüger et al., 2015). Soviet gymnasts, with their emphasis on artistry, flexibility, and innovation, revolutionized the sport, making gymnastics not only a display of physical prowess but also an artistic performance.

The late 20th century saw significant changes in the governance of sport, with the FIG updating the Code of Points to prioritize difficulty, execution, and artistic impression. This period also marked a shift in training methodologies, with greater attention to early specialization, injury prevention, and long-term athletic development (Al-Qahtani et al., 2023). Today, artistic gymnastics continues to be one of the most popular and prestigious sports in the Olympic Games. The sport has evolved into a highly technical discipline that combines strength, agility, and

artistic expression, with male and female gymnasts competing across different apparatuses and events. The emphasis on athletic difficulty, precision, and artistic performance remains at the core of artistic gymnastics, ensuring its ongoing development and appeal (Horne, 2016).

This sport consists in a variety of elements across different apparatus (e.g., floor, vault, uneven bars, balance beam for women; floor, pommel horse, rings, vault, parallel bars, and horizontal bar for men). These elements require a combination of strength, flexibility, coordination, and balance. For example, vaulting and floor exercises involve powerful take-offs and complex aerial skills, demanding explosive strength, precision, and stability during landings (M. Gittoes, Jr. & G. Irwin, 2012). Gymnasts must maintain a high level of flexibility to execute the required range of motion during complex movements such as splits, leaps, and flips, while coordination is critical for maintaining control during rotations and dismounts (Prassas et al., 2006).

When considering landings, these are a significant cause of injuries in artistic gymnastics, particularly to the lower extremities, due to the high impact forces absorbed by the joints upon contact with the ground. Ankle injuries, including sprains and fractures, are among the most common, often resulting from landings with errors on uneven surfaces or poor joint stabilization during dismounts (Kerr et al., 2010). Knee injuries, such as anterior cruciate ligament (ACL) tears, are also prevalent, particularly during high-impact landings that involve rotation or hyperextension (Hart et al., 2018). According to O'kane et al. (2011) hip injuries, though less common, can occur due to repetitive stress during landings and rapid changes in direction during elements like tumbling and vaulting. Proper physical preparation, including strength and stability training, is crucial to mitigate these risks and improve landing mechanics.

2.2 Biomechanics of Landings

Gymnastics landings can be broadly categorized into two types: single and both-leg landings. Both or double-leg landings are more common in artistic gymnastics, particularly during dismounts from apparatus and tumbling

sequences. They require the gymnast to absorb impact forces symmetrically through both legs, using strong eccentric muscle contractions in the quadriceps, gluteus, and triceps *surae* to control the descent and stabilize the body (McNitt-Gray et al., 2001). According to Wesley et al. (2015) single-leg landings, typically seen in beam dismounts and certain elements, are more challenging due to the reduced base of support, increasing the demand on balance, coordination, and the strength of the supporting limb.

Biomechanically, successful landings depend on controlled joint flexion, primarily at the ankle, knee, and hip joints, to distribute impact forces efficiently while maintaining balance. Gymnasts are trained to use their lower body muscles to decelerate their momentum and prevent excessive joint loading (Prassas et al., 2006).

Several studies have quantified the ground reaction forces (GRFs) during gymnastics landings, demonstrating the major stress placed on the body (Glynn et al., 2022; Seeley et al., 2005; Wu et al., 2019). GRFs during dismounts can reach up to 13 times the gymnast's body weight, especially in high-level skills like vaults and floor dismounts (Daly et al., 2001). These forces are primarily absorbed by the lower extremities, particularly at the ankle and knee joints. As Sands (2000) showed, the way in which a gymnast absorbs these forces is crucial for injury prevention, as improper landing techniques can lead to increased stress on the bones and soft tissues.

Some studies using force platforms have shown that the rate at which these forces are applied is also a critical factor (McNair & Prapavessis, 1999). Higher rates of force application, particularly during stiff or locked-knee landings can result in greater joint loading and increase the risk of injury (Devita & Skelly, 1992). Some landing mechanics, such as flexed knees and hips, help to reduce these forces and distribute them more evenly throughout the body (McNitt-Gray et al., 2001).

Several risk factors contribute to the incidence of injury during landings in WAG and MAG. Improper techniques, such as landing with extended knees or an

imbalanced posture, are one of the primary contributors to injuries. These faulty techniques can increase the load on the ligaments and bones, particularly in the knee and ankle joints (Tisano et al., 2022), leading to sprains, fractures, or even ligament tears. Fatigue is another significant risk factor, as it impairs neuromuscular control and coordination, making it more difficult for gymnasts to execute proper landing mechanics. As gymnasts become fatigued, they may exhibit less knee flexion and slower reaction times, resulting in stiffer landings with higher impact forces (Hewett et al., 2005).

Lastly, it is reported that insufficient preparation, including inadequate strength and mobility training, can predispose gymnasts to injury. A lack of strength in the lower extremities or core can impair the gymnast's ability to control deceleration during landings, leading to greater forces transmitted through the joints (Hughes et al., 2008). Preconditioning programs that emphasize strength, mobility, and neuromuscular control are described as critical for reducing injury risks associated with landings in gymnastics (Sands, 2000).

2.3 Physical preparation in Gymnastics

Physical conditioning is a cornerstone of both performance enhancement and injury prevention in gymnastics. Gymnasts must develop a combination of strength, power, endurance, flexibility, and balance to perform complex movements and skills. Conditioning programs are designed to improve the gymnast's ability to generate power for explosive movements like vaults and tumbling while simultaneously enhancing their capacity to stabilize and control landings, which are essential for safety and performance (Sands, 2000). Additionally, proper conditioning contributes to increased joint stability, reducing the likelihood of injuries caused by high-impact forces during landings (Hewett et al., 2005). Physical preparation protocols for gymnasts often emphasize exercises that enhance landing mechanics, strength, balance, and flexibility. These protocols typically include plyometrics, core strengthening, and proprioceptive training, all of which are tailored to meet the demands of gymnastics. For example, programs designed to improve landing mechanics focus on teaching gymnasts to absorb impact forces effectively by flexing their

hips, knees, and ankles during landings (McNitt-Gray et al., 2001). Specific protocols, such as neuromuscular training programs, aim to enhance muscle control and joint alignment, which are critical for injury prevention during high-impact landings (Hewett et al., 2005).

In a study by DiStefano et al. (2010), a specific training protocol involving plyometric drills, balance exercises, and technique correction was shown to significantly improve landing performance in young athletes, including gymnasts. Similarly, balance training is frequently included to help gymnasts stabilize during single-leg landings and reduce the risk of falls and lower extremity injuries (Waldhelm et al., 2022).

Strength training, especially in the lower extremities, enhances the muscles' ability to stabilize joints during dynamic movements and landings, reducing stress on ligaments and tendons. Studies have shown that well-conditioned leg muscles, particularly the quadriceps, hamstrings, and glutes, are crucial for controlling the deceleration phase during landings, thus minimizing the risk of injury (Myer et al., 2004). Plyometric training, which involves explosive, high-intensity movements like jumps and hops, has been widely used in gymnastics to improve power and coordination. Plyometrics enhance the body's ability to generate force quickly, which is essential for take-offs and controlled landings. Importantly, plyometric exercises teach athletes to absorb forces effectively by utilizing eccentric muscle contractions (Heiderscheit et al., 2010).

Research has demonstrated that athletes who engage in regular strength and plyometric training exhibit better neuromuscular control during landings and greater ability to dissipate impact forces, which are essential for injury prevention in gymnastics (Hughes et al., 2008). For example, a study by Hewett et al. (2005), found that plyometric and strength training reduced the incidence of knee injuries in female athletes by improving landing mechanics and enhancing lower limb muscle coordination.

2.4 Training interventions on landings

Training interventions of different durations, such as 6-week versus 12-week programs, can have varied effects on landing impact and performance in gymnastics or similar sports. Such as DiStefano et al. (2010), verified, short-term training, such as a 6-week intervention, typically focuses on the initial neuromuscular adaptations, including improved muscle recruitment and motor control, which can lead to reduced landing impact forces and better overall performance. However, the benefits might be less sustained unless followed by more prolonged training. In contrast, long-term interventions, such as 12-week programs, tend to show more significant improvements in muscle strength, endurance, and coordination, resulting in a greater capacity to manage high-impact forces over time (Hewett et al., 2005). These longer interventions often yield more robust structural adaptations like tendon stiffness and enhanced muscular power, which contribute to better landing mechanics and reduced injury risk (Myer et al., 2006).

Neuromuscular adaptations to training, such as balance training, core stability exercises, and strength training, are crucial for improving landing mechanics and reducing impact forces in gymnastics. Balance training helps enhance postural control, allowing gymnasts to stabilize their bodies more effectively during landings. Improved joint positioning reduce the risk of poor landings that could lead to injury (Zech et al., 2010). Core stability training, which focuses on the muscles of the abdomen, lower back, and pelvis, is vital for maintaining body alignment and preventing excessive motion during high-impact landings (Leetun et al., 2004).

Strength training, particularly in the lower extremities, contributes to improved neuromuscular control by increasing the capacity of muscles to absorb and dissipate landing forces. Studies show that athletes who engage in strength training develop greater control during eccentric movements, which is critical for managing the deceleration phase of landings (Ebben et al., 2010). This adaptation is particularly important for preventing injuries like anterior cruciate ligament tears, which are common in high-impact sports (Myer et al., 2004).

Recovery periods are essential for facilitating performance improvements and adaptation during a 6-week training protocol. Sufficient recovery allows the body to repair micro-damage to muscles and tissues and consolidate neuromuscular adaptations, leading to enhanced performance. In the context of gymnastics, incorporating recovery periods within a 6-week training program helps avoid overtraining, which can lead to fatigue, reduced motor control, and higher injury risk during landings (Bahr & Krosshaug, 2005b).

Active recovery methods, such as low-intensity exercises, can promote blood circulation and facilitate muscle recovery while maintaining flexibility. According to Sands et al. (2013), passive recovery, involving rest and relaxation, allows for full muscle repair and regeneration, preventing chronic fatigue that could undermine neuromuscular gains made during training. Optimally timed recovery intervals in short-term protocols are essential to ensure that athletes do not accumulate fatigue, which can impair performance and slow down the adaptation process (Williams et al., 2016).

2.5 Measures and evaluation of landing impacts

The most common evaluation methods include force platforms, motion capture systems, inertial measurement units (IMUs), and EMG. The accurate measurement of landing impacts in gymnastics relies on advanced tools and technologies designed to capture ground reaction forces, joint loading, and other biomechanical variables. One of the most used tools are the force plates, which are platforms embedded with sensors that measure the GRFs generated during landings. Force plates provide high-resolution data on vertical, medial-lateral, and anterior-posterior components of ground reaction forces (McNitt-Gray et al., 2001). These data are critical for understanding how different landing techniques affect joint loading and injury risk. Force plates are widely regarded as the gold standard for measuring GRFs due to their high sensitivity and accuracy. Research consistently demonstrates their reliability in capturing vertical and horizontal forces with minimal error (Jandacka et al., 2018). However, the validity of force plate data can be influenced by factors such as the athlete's foot

placement and the type of landing surface used, which must be carefully controlled during testing.

Motion capture systems are another essential technology, often used in synchronization with force plates. These systems employ multiple high-speed cameras with or without (markerless system) reflective markers placed on the athlete's body to track the three-dimensional movement of body segments during landing. The integration of motion capture with force plates data allows researchers to calculate joint angles, moments, velocities, and forces providing a comprehensive analysis of landing mechanics (Holden et al., 1997). However, the accuracy of these motion capture systems depends on the correct placement of markers and the calibration of the cameras. Errors in marker placement can lead to inaccuracies in joint angle measurements, affecting the validity of the data (Gäbler et al., 2018).

Wearable sensors, such as accelerometers and IMUs, are increasingly being used to measure landing impacts in real-world environments outside the laboratory. These devices can capture data on acceleration, angular velocity, and orientation, offering a more practical and accessible means of monitoring landing impacts in training settings (Bahr & Krosshaug, 2005). Sensors offer good reliability for measuring dynamic variables like acceleration and angular velocity, particularly in field settings. However, their validity may be limited compared to laboratory-based tools, as they are susceptible to noise and movement artifacts. According to Bahr and Krosshaug (2005), despite these limitations, advances in sensor technology and data processing algorithms are improving their accuracy, making them increasingly valuable for real-world applications.

Several key metrics are used to evaluate landing performance, with peak force being one of the most critical. Peak force refers to the maximum ground reaction force recorded during landing and is a direct indicator of the impact's severity. High peak forces are associated with increased risk of injury, particularly to the lower extremities (Hewett et al., 2005). Another important metric is the rate of force development (RFD), which measures how quickly force is applied during

the landing. A rapid RFD can indicate a stiff landing, which increases joint loading and injury risk. Conversely, a slower RFD suggests better force absorption, which is generally more desirable (McNitt-Gray et al., 2001). Joint angles at the ankle, knee, and hip during landing are also crucial variables. These angles reflect the athlete's ability to flex and absorb impact forces effectively. Smaller knee flexion angles, for example, are associated with higher impact forces and greater injury risk (Myer et al., 2006). Stability, often assessed through measures like center of mass displacement or postural sway, is another key performance metric. Stability metrics indicate how well the gymnast can maintain balance upon landing, with greater stability reflecting better neuromuscular control and lower injury risk.

2.6 Previous research in other sports

Sports like basketball and volleyball involve frequent landings with high GRFs, making them comparable to gymnastics in terms of impact demands. Studies in basketball, for example, show that landing mechanics, such as knee valgus and poor hip control, contribute to ACL injuries, much like in gymnastics (Hewett et al., 2005). Volleyball players also experience high GRFs during repeated jumps and landings, with evidence suggesting that proper neuromuscular training reduces the impact forces and injury risk, particularly in the lower extremities (Chappell & Limpisvasti, 2008). These findings highlight that many of the biomechanical principles and injury risks observed in gymnastics are consistent with those seen in other sports.

Training methods from other sports, such as plyometrics and neuromuscular training used in basketball and volleyball, can be adapted to gymnastics to improve landing mechanics and reduce injury risks. Plyometric training, which enhances muscle power and force absorption, has been shown to decrease peak GRFs and improve stability during landings in basketball and volleyball athletes (Myer et al., 2006). Additionally, proprioceptive and balance training, commonly used in soccer and volleyball, can be incorporated into gymnastics training to improve control during single-leg landings, which are prevalent in gymnastics (Grooms et al., 2013). By drawing on interdisciplinary approaches, gymnastics

training can integrate successful strategies from other sports to mitigate landing impacts and prevent injuries.

2.7 Previous research in gymnastics

Several studies have implemented specific training interventions in gymnastics aimed at improving landing performance and reducing injury risk. For example, Myer et al. (2006) found that a 6-week neuromuscular training program significantly improved landing mechanics and reduced knee valgus angles in female athletes, a key factor in reducing ACL injuries. Similarly, Hewett et al. (2005), demonstrated that plyometric and balance training led to improved joint alignment and reduced injury risk in sports involving high-impact landings, which has direct implications for gymnastics. Hewett et al. (2005), showed that gymnasts who underwent balance and proprioceptive training exhibited better control during landings, resulting in lower GRFs and reduced risk of lower extremity injuries. Additionally, a study by McNitt-Gray et al. (2001), highlighted that strength and conditioning programs aimed at improving eccentric control could help gymnasts manage the high impact forces typical of landing maneuvers, thus lowering injury risk.

The literature on training interventions to improve landing performance and reduce injury risk in gymnastics and related sports consistently highlights the benefits of neuromuscular and load training, plyometrics, and balance exercises (Zech et al., 2010). These interventions have been shown to reduce GRFs improve joint alignment, and decrease injury risk, particularly in the lower extremities. Short-term interventions, such as 6- to 10-week programs, have produced measurable improvements in landing mechanics, including reduced knee valgus angles and enhanced eccentric control (McNitt-Gray et al., 2001). However, there are key gaps, particularly in long-term studies and research specifically tailored to the unique demands of artistic gymnastics landings, which involve single-leg landings and complex aerial maneuvers (Sands et al., 2013).

The proposed 6-week specific physical preparation protocol aims to address these gaps by focusing directly on artistic gymnastics-specific landings, incorporating strength, plyometric, and proprioceptive exercises designed to improve force absorption, balance, and overall control. By tailoring the intervention to the unique biomechanical demands of gymnastics, this protocol seeks to provide more precise and applicable outcomes than previous generalized studies, contributing to the limited body of research on gymnastics-specific training.

3. Article 1

THE IMPACT OF LANDINGS AND GROUND REACTION FORCES IN ARTISTIC GYMNASTICS: A SYSTEMATIC REVIEW

Abstract: *There has been a growing concern about the technical execution of gymnastics landings due to the impacts experienced by gymnasts repeatedly and the consequences that may be associated with it. The majority of artistic gymnastics exercises end in a landing where gymnasts are exposed to a very high ground reaction forces. The aim of this review was to identify and synthesize the available scientific literature addressing the landing ability on different apparatus from artistic gymnastics. Between 11 to 21 of May 2022, research about this topic based on 4 databases: SCOPUS, Web of Science, EBSCO and PubMed found 16 articles excluding duplicates and articles marked as ineligible by automation tools. This sport should have an increment of specific research to provide all specialists and coaches a wide range of knowledge about the specific characteristics of landings in all 4 apparatus, and to provide information about the correct way to improve this specific movement in training context. Physical preparation and the ideal conditions for landings execution must be the subject of a lot of research. This greater quantity and quality of information could give coaches more tools to implement effective practice exercises in order to have a positive impact in gymnastics development.*

Keywords: *Artistic Gymnastics, Landings, Ground reaction forces, Biomechanics*

1 INTRODUCTION

Research in artistic gymnastics has been extensive since the sport's initial development, but there has been a continuous growing interest and increased research since the first participation in 1928 Olympic Games, in Amsterdam, by both men and women. Since this heyday, artistic gymnastics has gained a growing interest from the scientific community to understand the biomechanical components of the complex movements of this sport, but also the physiological phenomena of its athletes (Prassas et al., 2006). From 2000 onwards there has been an exponential development of scientific research, and the papers found on this area of gymnastics are now vaster and more diversified.

In gymnastics, all exercises end in a landing and, therefore, a proper and safe landing is a crucial element of gymnastics events (Niespodziński et al., 2021). According to Nagano et al. (2009), about 69-84% of landings are performed with a failure rate which can then lead to injury. Peak vertical ground reaction forces exceeding nine bodyweights and occurring in less than 0.05 seconds have been reported by Niespodziński et al., (2021), which gives us the perception that massive efforts are experienced by gymnasts when these landings occur.

The quality of landing depends on subjective (e.g., biomechanical) and objective (e.g., mechanical characteristics of landing area) factors (Cuk & Marinšek, 2013) but also depends a lot on the athlete's motor control and physical preparation.

With physical preparation, we are referring the gymnast's ability to deal with the loads that they are exposed during the landing. So, the lack of a good conditioning and physical preparation constrains the success of well performed landings, which in the long term can lead to overuse injuries. By motor control we consider the control that the gymnast exercises over the skill she performs, such as the body-space notion and flight time of the same (Cuk & Marinšek, 2013).

Since every routine in all 4 apparatus in Women Artistic Gymnastics (Mizutori et al., 2021) and in all 6 apparatus in Men Artistic Gymnastics (Kara et al., 2023) ends with a landing, this part of the movement takes a major role in the final punctuation of each exercise. The final score of each apparatus dictates if the performance of the gymnast was better or worse, therefore an improvement in the gymnast performance is measured by the final punctuation in each routine.

According to 2022-2024 code of points the final punctuation of each routine is influenced by penalizations that come from technique errors from difficulty of the elements that composes each routine (FIG, 2022). Therefore, the more successful a landing is, the smaller are the penalties that result from this, in the final routine score.

The improvement in landing technique combined with proper physical preparation ensure that landings are safer and have a higher success rate, leading to an improvement in gymnasts' performance.

The research about artistic gymnastics is distributed in several sports journals. The aim of this review was to identify and synthesize the available scientific literature addressing the landing ability on different apparatus from artistic gymnastics based on different methods of evaluation. This allows to organize this information in distribution by themes, areas of analysis and used methods. This information is very useful to help coaches in the process of teaching correct and safer landings, improve the technique of these movements and, therefore, enable gymnasts to achieve a better performance in competitions.

2 METHODS

2.1 Search Strategy: Databases, Inclusion Criteria and Selection Process

A systematic review of the available literature was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guide- lines (Page et al., 2021). The research strategy adopted in the current study was followed by Sarmento, Anguera, Pereira, and Araújo (2018). This systematic literature review was performed based on 4 databases: Scopus, Web of Science, Ebsco and PubMed and all of them were subject to a deduplication and screening process via Endnote X20 (Clarivate Analytic, Philadelphia).

A search in the databases was conducted between 11 to 21 of May 2022, using a filter for the inclusion of scientific articles and search in sports journals. The following search key was used: "Artistic Gymnastics AND Landing AND Ground reaction forces".

The inclusion criteria for the chosen articles were (1) to include relevant data about technical components of landings in gymnastics; (2) to approach different forms and methods of studying ground reaction forces in this sport; (3) to include athletes with previous experience in artistic or acrobatic gymnastics in specific cases of floor elements (not discarding Men's Artistic Gymnastics, because we believe that the articles of this male component can have a lot of interest, influence and transfer to many aspects of the Women's Artistic Gymnastics too); and (4) articles published in English or Portuguese.

Studies were excluded if they (1) did not focus on elements with specific transference to the Artistic Gymnastics; (2) did not use any athletes from Artistic Gymnastics; and (3) did not include any relevant data about landings or ground reaction forces.

After this analysis we started the process of removing duplicates using Endnote 20. The final part of this process consisted of organizing and cataloging the articles by subject, in the "manage attachments" function, where attachments can be viewed, sorting the files by file name, author name, year of publication and title. Later we gathered all this information in a word document, and well-ordered the different themes by numbers and topics.

2.2 Extraction of Data and Quality of the Studies

Quantitative studies were analyzed to determine if they included the following 16 items that dictate the quality of the studies: purpose (item 1), relevance of background literature (item 2), appropriateness of the study design (item 3), sample included (items 4 and 5), informed consent procedure (item 6), outcome measures (item 7), validity of measures (item 8), significance of results (item 10), analysis (item 11), clinical importance (item 12), description of drop-outs (item 13), conclusion (item 14), practical implications (item 15) and limitations (item 16).

The outcomes per item were 1 (match the criteria), 0 (does not match the criteria fully), or NA (not applicable).

In order to make a fair comparison between studies with different designs, we decided to calculate a percentage score as a final measure of methodological quality. The sum of the scores of all items was divided by the number of relevant scored items for that specific research design. All articles were classified as (1) low methodological quality, with a score lower than 50%; (2) good methodological quality, with a score of between 51 and 75%, and (3) excellent methodological quality, with a score bigger than 75%. First, one researcher extracted the data from included studies and a second researcher then checked the extracted data. Disagreements were resolved by consensus between these two authors.

3 RESULTS

3.1 Search, Selection and Inclusion of Publications

The initial search identified 754 titles in the described databases. These data were then exported to reference manager software (EndNote X20). Any duplicates (82 references) and articles marked as ineligible by automation tools (16 references) were automatically removed. The remaining 656 articles were then screened according to the title and abstract for relevance, resulting in another 572 articles being eliminated manually and by automation tools from the database. The text of the remaining 84 articles were selected for in-depth reading and analysis (Prisma Flo diagram – Fig 1).

The main factor for study exclusion ($n = 28$) was their nonrelation to the sport in analysis. Other studies were excluded because they contained data from participants from other sports ($n = 23$) and because of their lack of relevance to the research topic, due to the lack of practical application of this review ($n = 17$). The final phase lead us with 16 studies to be included in this review.

3.2 Quality of the Studies

Concerning the quality of studies, the most noteworthy results were that the mean score for the 16 selected studies was 93,7%. Two publications achieved the maximum score of 100%; 0 publication scored below 50%; 0 studies scored

between 51 and 75%; and 14 publications achieved an overall rating of more than 75% of quality.

Two independent reviewers independently classified the papers according to the different major research topics. “Was the study purpose stated clearly? Was relevant background literature reviewed? Was the design appropriate for the research question? Was the sample described in detail? Was sample size justified? Was informed consent obtained? Were the outcome measures reliable? Were the outcome measures valid? Was the method described in detail? Were results reported in terms of statistical significance? Were the analysis methods appropriate? Was importance for the practice reported? Were any dropouts reported? Were conclusions appropriate given the study methods? Are there any implications for practice given the results of the study? Were limitations of the study acknowledged and described by the authors? Disagreements were solved through discussion with the other co-authors until a consensus was found. The aim was not to produce categories that were mutually exclusive since the same analysis can include topics that relate to different categories. Thus, an article included in a specific ‘category’, could also be classified in another ‘category’ whenever its content justified it.

Prisma Flow Diagram

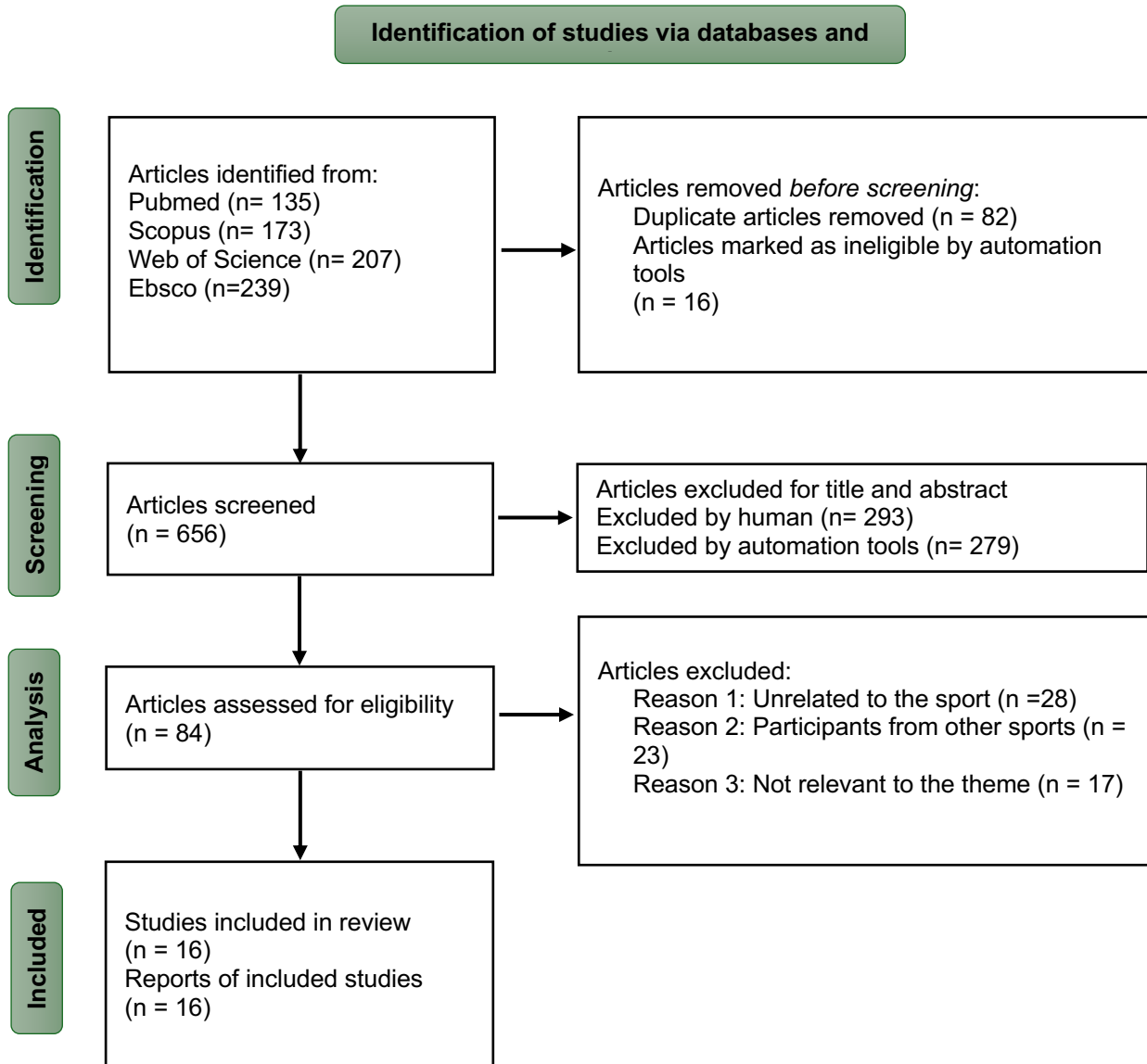


Figure 1. Prisma Flow Diagram of the procedures used for the article search.

3.3 General Description of the Studies

Landings in gymnastics and their impact on athlete's performance have been the topic for 16 studies. The main division in the analysis of these studies was about the procedure used in the methodology, which we separate in (1) studies using only force plates; (2) studies using detailed image analysis; (3) studies using EMG, force plates and detailed image analysis; and (4) other many different methods.

Table 1 shows the main topics of the studies included in this review that used force plates as the main procedure for the research.

Table 1
Studies using only force plates.

Study	Sample	Procedure	Results and conclusions	Quality score (%)
Glynn et al. (2022)	32 asymptomatic Elite level gymnasts from 3 artistic gymnastic teams. 15 Senior F - 10 Junior F - and 7 Senior M	3 “drop jumps” off the step completing a 180 turn in the air and landing with both feet on the force plate.	No statistical difference between injured and non-injured gymnasts for landing force (p 1/4 0.481) and asymmetry of landing force (p 1/4 0.698). Most participants (69%) demonstrated inter-limb asymmetry of landing forces, observed in injured and uninjured gymnasts. Both magnitude of landing force and inter-limb asymmetries of landing force failed to identify the risk of ankle injury.	93,3
Seegmiller and McCaw (2003)	20 F students between 18 -23 years. 10 members of Division I team with at least 8 years of gymnastics experience. 10 recreational athletes that had a previous involvement in organized group sports.	10 trials of 30, 60 and 90 cm drop jumps on to a force plate.	Gymnasts exposed themselves to higher GRF at 60 and 90 cm than recreational athletes. Gymnasts land with higher impact forces than recreational athletes, raising concerns for repetitive stress injuries because of high-impact loading.	93,3
Seeley and Bressel (2005)	10 high-level F gymnasts competing at level 9, 10 or elite ranked by the USA Gymnastics Federation). 8 collegiate level gymnasts. 2 competitive gymnasts that could successfully perform the Yurchenko vault.	3 trials of Yurchenko vault and round-off on floor with the trail hand contacting a force platform.	Vertical and anterior-posterior GRF, normalized to body weight, were greater (p < 0.05) during the round-off phase of the Yurchenko vault (2.38) than during the floor exercise round-off (2.15). Vertical GRF during both round-off exercises are similar to reaction forces transmitted to upper extremities during other gymnastic skills to lower extremities while running and walking at various speeds.	93,3
Straker et al. (2022)	7 F, competitive, collegiate, artistic gymnasts (age: 20.5 ± 1.2 years) non injured and actively training at least 3 times per week at a University gymnastics club.	20 drop landings from a 0,72m box onto 2 force plates covered with 2 gymnastics mats.	Group differences (p ≤ .05) reported in the sagittal ROM at the knees and hips, with the men’s strategy eliciting a larger ROM decelerating the body upon impact. Individually favored landing strategy to fulfil the informational constraints and hence supporting the use of a single-subject design. emphasizes the potential injury risk associated with the different informational constraints placed on F landing strategy by the FIG, whilst recognizing the individual gymnasts’ task response.	100

Female (F), Ground Reaction Forces (GFR), Male (M), Range of Motion (ROM)

Concerning the studies described in Table 1, only one used a sample with both sexes (Glynn, Laird, Herrington, Rushton, & Heneghan, 2022) and the other three used a sample of female athletes (Seegmiller & McCaw, 2003; Seeley & Bressel, 2005; Straker et al., 2022). Two articles had samples with 10 or less athletes (Seeley & Bressel, 2005; Straker et al., 2022), and two articles had samples with more than 10 athletes (Glynn et al., 2022; Seegmiller & McCaw, 2003). All four articles had gymnasts in their samples, three of them referred that gymnasts were competing in collegiate teams in the season when the research occur (Seegmiller & McCaw, 2003; Seeley & Bressel, 2005; Straker et al., 2022) and the fourth one had gymnasts classified as Elite such as Glynn et al. (2022).

In all the studies that used only a force plate as an evaluation instrument for ground reaction forces (GRF), gymnasts performed different types of tasks when contacting the force platform. The majority of them evaluated the final phase of a movement, such as a landing with both feet after a 180° turn from a step seen in Glynn et al. (2022), 30, 60 and 90 cm drop jumps seen in Seegmiller and McCaw (2003) and drop jumping from a 0,72 m box seen in Straker et al. (2022). In Seeley and Bressel (2005) the participants were evaluated in the first part of the movement during the Yurchenko vault and round-off on floor with the trail hand contacting the force platform.

Three articles showed significant differences in their results (Seegmiller & McCaw, 2003; Seeley & Bressel, 2005; Straker et al., 2022) and one showed no difference for landing force and asymmetry of landing force (Glynn et al., 2022). Glynn et al. (2022) results showed inter-limb asymmetry of landing force both in injured and uninjured gymnasts. In other article, Seegmiller and McCaw (2003) results showed that gymnasts land with higher impact forces than recreational athletes. Analyzing the same skill Seeley and Bressel (2005) results showed that vertical and anterior-posterior reaction forces, normalized to body weight, were greater during the round-off phase of the Yurchenko vault than during the floor exercise round-off. Additionally, (Straker et al., 2022) reported differences between groups in the sagittal range of motion (Straker et al.) at the knees and hips, with the men's landing strategy eliciting a larger ROM decelerating the body upon.

Table 2 shows the main topics of the studies included in this review that used image analysis as the main procedure for the research.

Table 2
Studies using detailed image analysis

Study	Sample	Procedure	Results and conclusions	Quality score (%)
Cuk and Marinšek (2013)	12 M gymnasts from the Slovenian national gymnastics team (Age: 18.75 ± 2.63 years).	1 stretched forward and backward salto with $\frac{1}{2}$, $\frac{1}{1}$ and $\frac{3}{2}$ turns on a competition floor, with 24 Parotec hydrocell pressure sensors for each foot and three video high quality cameras	Average deduction for landing was 0.30 points, which can be described as an average error. All analyzed predictors defined asymmetries between lower limbs (speeds and angles).	93,3
Mizutori et al. (2021)	59 M gymnasts (Age: 16.4 ± 2.9 years), including 48 junior elite national gymnasts in national training camp.	2 straight arm press to handstand on a force platform with image capture using a video camera (Basler AG, Type A602fc-2).	Larger shoulder flexion moments observed in less-skilled compared with highly- skilled performers. Larger hip flexion moments were observed in highly- skilled performers at 52% and normalized time of straight arm press to handstand. Major differences between highly skilled and less-skilled performers were observed in hip joint moment production as it shifted from extension to flexion from the leg horizontal position to the handstand position in highly skilled gymnasts.	93,3

Male (M)

Concerning the studies using detailed image analysis, both used samples with male gymnasts (Cuk & Marinšek, 2013; Mizutori et al., 2021), one with 12 gymnasts (Cuk & Marinšek, 2013) with an average age of 18.75 ± 2.63 years, and one with 59 gymnasts (Mizutori et al., 2021) with an average age of 16.4 ± 2.9 years. Both samples had gymnasts in National teams (Cuk & Marinšek, 2013; Mizutori et al., 2021).

A stretched forward and backward salto with $\frac{1}{2}$, $\frac{1}{1}$ and $\frac{3}{2}$ turns on a competition floor were evaluated (Cuk & Marinšek, 2013), as well as a two straight arm press to handstand (Mizutori et al., 2021). One movement was analyzed with just one high quality camera (Mizutori et al., 2021) and another one with 3 cameras (Cuk & Marinšek, 2013).

Both articles showed significant statistical differences in their results (Cuk & Marinšek, 2013; Mizutori et al., 2021). Cuk and Marinšek (2013) results showed that all predictors under analysis defined asymmetries between the legs (speeds and angles) and Mizutori et al. (2021) results showed that major differences between highly skilled and less-skilled performers were observed in hip joint moment production as it shifted from extension to flexion from the leg horizontal position to the handstand position in highly skilled gymnasts.

Table 3 shows the main topics of the studies included in this review that used a combination of three methods: (1) EMG, (2) force plates and (3) detailed image analysis.

Table 3
Studies using EMG, force plates and detailed image analysis

Study	Sample	Procedure	Results and conclusions	Quality score (%)
(Niespodziński et al., 2021)	46 M Elite-oriented gymnasts that had started training at the age of 6–7 years 58 M non-athletes age matched. G1: 8–10-year-olds, G2: 12–14-year-olds and G3: 18– 25-year-olds.	3 counter movement jumps on to a force plate with simultaneous surface electromyography (SEMG) recording.	Gymnasts achieved 13% higher values ($p = 0.04$) of relative peak GRFs in comparison with controls. It was especially seen in 8–10-year-olds: G1 presented 33% higher ($p = 0.03$) results than C1 and G2. Gymnasts aged 8–10 years showed the highest relative peak GRFs, as well as its rate of development.	93,3
(C. L. Wu et al., 2019)	17-Year-old international-level M gymnast from the Chinese artistic national team competing in World Cups, with no musculoskeletal injuries for at least 6 moths prior.	3 backward somersaults in a force plate with synchronized motion capture system (Qualisys Oqus) and a surface electromyogram system.	Different symmetry in kinematics, kinetics and EMGs between the left and right legs occur during the landing. In the impact phase the difference between flexions of both hip and knee joints was within 5 degrees and the difference in ankle dorsiflexion was within 10 degrees. the absolute symmetry index (ASI) of flexion lower limb joints were less than 10%.	93,3
(Król et al., 2020)	11 healthy artistic gymnasts (9 F and 2 M) members of the Polish national gymnastics team.	1 TS, 1 PS, 1 HS and a CMJ recorded with 6 infrared cameras, synchronized with a module for wireless EMG activity of 8 muscles, and 1 force plate.	CMJ showed the highest level of vertical impulse, velocity, and displacement followed by the TS, PS, and HS. In the take-off phase of Jumps with rotation the average muscle activation levels of the biceps femoris were significantly higher and of the rectus femoris significantly lower than in the CMJ.	93,3
(C. Wu et al., 2019)	6, 17 years old international-level M gymnast from the Chinese artistic national team competing in World Cups, with no musculoskeletal injuries for at least 6 moths prior.	3 BS in a force plate with synchronized motion capture system (Qualisys Oqus) and a surface electromyogram system.	In BS landings gymnast's 1st extend their lower extremity joints to increase the moment of inertia, and reducing the body's angular velocity before touchdown. The lower extremity joints flex actively just before touchdown, continue flexing actively and rapidly in the initial impact phase, and then extend to resist the impact force and maintain body posture during the terminal impact phase of the landing.	93,3
(Mills et al., 2008)	1 M Elite Gymnast with 1,77m and 75 kg.	Gymnast performed 1 forward rotating and backward rotating vault using a force place on the landing area, EMG and three-dimensional motion data using 12 Vicon 624 cameras.	High levels of co-contraction occur prior to landing. As there were already high activation levels the eccentric muscle forces were immediately large, but the concentric forces rapidly fell due to the fact that the muscles were shortening rapidly. This gave a rapid rise in the net extensor torque necessary to control the landing and this effect is likely to have occurred during the landing for the subject.	93,3

Backward somersaults (BS), Countermovement jump (CMJ) Female (F), Ground Reaction Forces (GFR), Male (M), Piked backward somersault (PS), Surface electromyography (SEMG), Tucked somersault (TS).

Concerning the studies described in table 3, only one used a sample with both sexes (Król, Klyszcz-Morciniec, & Bacik, 2020) and the other four used a sample with just male athletes (Mills et al., 2008; Niespodziński et al., 2021; C. Wu et al., 2019; C. L. Wu et al., 2019). Two articles had samples with case studies (1 athlete) (Mills et al., 2008; C. L. Wu et al., 2019), one article had samples with 6 athletes (C. Wu et al., 2019) and two articles had samples with more than 10 athletes (Król et al., 2020; Niespodziński et al., 2021), the first with 11 and the second with 46. Three studies included gymnasts that were part of national teams (Król et al., 2020; C. Wu et al., 2019; C. L. Wu et al., 2019) and the other two had elite-oriented gymnasts (Mills et al., 2008; Niespodziński et al., 2021) the first one had also age-matched non-athletes as part of control groups.

Three articles analyzed floor elements such as somersaults (Król et al., 2020; C. Wu et al., 2019; C. L. Wu et al., 2019), one analyzed vault elements (forward and backward) (Chris Mills et al., 2008) and one analyzed nonspecific gymnastics movement (counter movement jump) (Niespodziński et al., 2021). All articles showed significative statistical differences in their results (Król et al., 2020; Mills et al., 2008; Niespodziński et al., 2021; C. Wu et al., 2019; C. L. Wu et al., 2019). Niespodziński et al. (2021) results showed that gymnasts achieved 13% higher values ($p = 0.04$) of relative peak GRFs in comparison with controls, C. Wu et al. (2019) results showed that the absolute symmetry index (ASI) of flexion lower limb joints were less than 10% which showed an excellent landing symmetry in sports performance, Król et al. (2020) results showed that the countermovement jump (CMJ) showed the highest level of vertical impulse, velocity, and displacement followed by the tucked backward somersault (TS), piked backward somersault (PS), and backward handspring (Ebben et al.). C. L. Wu et al. (2019) results showed that the lower extremity joints flex actively just before touchdown, continue flexing actively and rapidly in the initial impact phase, and then extend to resist the impact force and maintain body posture during the terminal impact phase of the landing and Chris Mills et al. (2008) results show that the muscle activation profiles revealed fairly high levels of co-contraction prior to landing. Table 4 shows the main topics of the studies included in this review that used different methods for the research.

Study	Sample	Procedure	Results and conclusions	Quality score (%)
Sonvico et al. (2019)	30 Elite gymnasts (15 M, 15 F) between the ages of 16 to 30 years members of the British Artistic Gymnastics elite senior and junior training program.	Lumbar spine and LLS ROM during a SLT were measured, using the Dorsa Vi: Vi Perform™ system.	Maximal lumbar spinal movements were 64.23° (6.34°) for flexion and 25.89° (11.14°) for extension. During the SLT, participants performed lumbar spine flexion of 15.96° (8.80°), when considered as a single segment. When considering the lumbar spine as a two-segment model the LLS position during the SLT was towards end.	93,3
Rohleder and Vogt (2019)	25 M gymnasts with 16 years of age competing in World Championships. (WC13),(WC15),(WC17).	All floor exercise routines (n = 25) performed in the men's floor exercise finals at the World Championships in 2013 (WC13), 2015 (WC15) and 2017 (WC17) were examined using video analysis and official judges scores	Current changes in world elite floor exercise gymnasts are characterized by generally decreased score levels due to recent rule changes in the current punctuation code (2017). Focus on stick landings is particularly recommended, however current trends in composing floor exercise routines lead to increased landing errors and, thus lead to decreased final scores.	86,7
Kirialanis et al. (2003)	162 gymnasts (83 M and 79 F athletes) participating in the Greek artistic gymnastics' championships.	Gymnasts were observed during 1999-2000 season with personal consultations to register any injury occurring during competitions or training.	A total of 151 injuries were reported for the 12-month experimental period. 93 (61.6%) acute injuries and 58 (38.4%) overuse syndromes. The rate of mild injuries was 26.8% (25 cases), that of moderate injuries was 44% (41 cases), and that of major injuries was 29% (27 cases) (no significant difference between them).	92,9
Mills et al. (2009)	1 subject-specific 7 link wobbling mass model of a gymnast.	A 7-link wobbling mass model representing the gymnast was constructed in visualNastran 4D (VN4D) to simulate the first 100 ms of landing on a competition gymnastics mat. Experimental exercises were forward (FS) and backward rotating somersault (BS) vaults.	The successful minimization of ground reaction forces (GRF) during landing led to higher internal loading than the matching simulation. Minimizing internal bone bending moments gave low peak GRF with an initial time history that looked more similar to the matching performance.	92,9
Mills et al. (2010)	A multi-layer model of a gymnastics competition landing mat and a subject-specific 7 link wobbling mass model of a gymnast.	The gymnast-mat model has been evaluated from experimental forward (FS) and backward rotating somersault (BS) vaults.	The optimization of 6 landing mat parameters (± 20 % bounds) for the FS and BS vault resulted in the peak GRF being reduced. Gymnast model maintained an acceptable landing technique according to the F.I.G. criteria. The stiffness of the current competition landing mat is optimum and a 20 % change in landing mat damping results in only a small reduction in internal forces within the gymnast. Increased mat damping may be associated with increased forefoot loading.	100

Backward somersault (BS) Female (F), Forward somersault (FS), Ground Reaction Forces (GFR), Low lumbar spine (LLS), Male (M), Range of motion (Straker et al.), Simulated landing task (SLT).

Concerning the articles described in the fourth table, two of them had samples with both men and women (Kirialanis et al., 2003; Sonvico et al., 2019), one had

a sample with just men (Rohleder & Vogt, 2019) and two used a wobbling mass model of a gymnast as their subject (Mills et al., 2009; Mills et al., 2010). Two articles had samples with 30 or less athletes (Rohleder & Vogt, 2019; Sonvico et al., 2019) the first with 30 and the second with 25 athletes, and one had a sample of 162 athletes (Kirialanis et al., 2003). Besides the wobbling mass models of gymnasts used by C. Mills et al. (2009) and C. Mills et al. (2010), the other three articles had gymnasts in their samples participating in international championships (Kirialanis et al., 2003; Rohleder & Vogt, 2019) and members of National Elite teams (Sonvico et al., 2019).

Two articles analyzed a wobbling mass model of a gymnast using a computer program called *VisualNastran 4D* (Mills et al., 2009; Mills et al., 2010), one article analyzed routines using video analysis and official judges scores (Rohleder & Vogt, 2019), one used a longitudinal method where gymnasts were observed during 1999-2000 season with personal consultations to register any injury (Kirialanis et al., 2003), and one used the *Dorsa Vi: Vi PerformTM* system that measured lumbar spine and low lumbar spine (LLS) range of motion (Straker et al.) during a simulated landing task (SLT) (Sonvico et al., 2019).

Sonvico et al. (2019) results showed that during the SLT, participants performed lumbar spine flexion of 15.96° (8.80°), when considered as a single segment. When considering the lumbar spine as a two-segment model, the LLS position during the SLT was towards the end range anterior pelvic tilt, suggesting LLS extension. Rohleder and Vogt (2019) results showed that elite floor exercise gymnasts are characterized by generally decreased score levels due to recent rule changes in the punctuation code of 2017. (Kirialanis et al., 2003), results showed that the rate of small injuries was 26.8% (25 cases), the moderate injuries rate was 44% (41 cases), and the rate of major injuries was 29% (27 cases). The successful minimization of GRF during landing led to higher internal loading than the matching simulation (C. Mills et al., 2009). Mills et al. (2010) results showed that the optimization of six landing mat parameters ($\pm 20\%$ bounds) for the forward and backward rotating vault resulted in the peak ground reaction forces being reduced.

4 DISCUSSION

The aim of this review was to identify and synthesize the available scientific literature addressing the landing ability on different apparatus from artistic gymnastics based on different methods of evaluation. This review also intends to provide artistic gymnastics coaches relevant information about how to improve landing techniques and consequently their gymnast's performance. After in-depth analysis, it was decided that the most appropriate way to discuss the results would be to categorize research topics according to the procedure used in the methodology (Only force plates; Detailed image analysis; EMG, force plates and detailed image analysis together and other different methods).

4.1 Force plates

Force platforms assessment has been used to examine impact forces and injury risk in several gymnastics' tasks (Glynn et al., 2022; Seegmiller & McCaw, 2003; Seeley & Bressel, 2005; Straker et al., 2022). According to Leite et al. (2023) recent research about biomechanics in gymnastics actually shows that the most used instrument in Acrobatic Gymnastics is the force platform, similar to what happens in Artistic Gymnastics.

Data from the reviewed studies showed that both sexes were used in the analyzed samples, proving that Women Artistic Gymnastics (Mizutori et al., 2021) and Men Artistic Gymnastics (Kara et al., 2023) gymnastics have transference and similarity in several exercises. However, Straker et al. (2022) proves that men and women have different landing strategies which led to differences in the sagittal range of motion (Straker et al., 2022) at the knees and hips, with the men's landing strategy eliciting a larger ROM decelerating the body upon impact. In the WAG's code of point, any leg separation, smaller or larger is considered an error following the landing of an acrobatic element, with 0,1 deducted from the final execution score on every occasion (Fédération Internationale de Gymnastique, 2022). The differences in landing technique between WAG and MAG gymnastics may have several implications regarding the incidence of traumatic knee and ankle injuries, particularly within the female competition (Kerr et al., 2015).

These results indicate an individually favored landing strategy to fulfil the informational constraints and hence supporting the use of a single- subject design (Straker et al., 2022). This also emphasizes the potential injury risk associated with the different informational constraints placed on female's landing strategy by the FIG code of points, whilst recognizing the individual gymnast's task response. A further analysis of the FIG code of point, and its penalizations could allow to prevent the risk of certain "unhealthy" movements. For instance, allowing a larger degree of leg separation may allow female gymnasts to suffer less painful, less impactful, less constrained and more stable landing strategy (Straker et al., 2022) which could be enhanced by coaches in practice.

In the analyzed studies all the samples had the minimum age of 14 years old, since only Junior and Senior athletes were evaluated. This older age range of the athletes ensures more experience in the sport, many hours of weekly training such as reported by Seeley and Bressel (2005) (> 20 hours of practice per week) and so a guaranteed proficiency in the elements that were being evaluated.

In our results 3 articles provided wide information about the sample characterization (Seegmiller & McCaw, 2003; Seeley & Bressel, 2005; Straker et al., 2022) such as sex, age, years of experience, competitive level, years/hours of practice, which gives us interesting information for analyzing these athletes' performance in the evaluated exercises. However, in Glynn et al. (2022) article the sample was only characterized by sex, age and anthropometrics. We consider that this lack of relevant information regarding the athlete's experience and volume of practice makes the interpretation of the results presented in their study and the practical implications of its conclusions more difficult.

Regarding the procedure used in these articles, drop jumps were the most used exercises in force platform analysis, because of their well-controlled experimental approach. This is a common exercise used to recreate rapid impact forces experienced in gymnasts' lower limbs during landings (Fransz et al., 2013). However only one study evaluated in its procedure two specific gymnastics movements (Seeley & Bressel, 2005), the *Yurchenko* vault and round-off on floor with the trail hand contacting the force plate. These movements were thoroughly analyzed and provided information about the specific way to improve

the technique and quality of the movement without speculations or generalizations.

When comparing some elements of different apparatus that have similar patterns of moment, such as the round-off phase of the Yurchenko vault and the floor exercise round-off the Seeley and Bressel (2005) results showed that vertical and anterior-posterior reaction forces were greater in the Yurchenko but both skills showed high reaction forces.

These differences may occur because the approach distance in Yurchenko vault and floor round-off are different, being 20 meters in the first and approximately 7 in the second. Shorter approach distances during the floor exercise indicate less opportunity to accelerate, resulting in lower velocities at the time of the round-off (Seeley & Bressel, 2005). There is also an important difference in the final portion of each skill which are the limits of the routine area. Gymnasts performing round-off on the floor are required to stay within the limits of the floor routine area and penalized for leaving the established bound (Fédération Internationale de Gymnastique, 2022), while gymnasts performing the Yurchenko vault have no such limits and are encouraged to vault as far and high as possible.

This data shows the urge for further research considering methods to reduce reaction forces in the upper limbs during floor exercises, such as the Yurchenko vault and other gymnastics skills where gymnasts are exposed to this type of loads.

Seegmiller and McCaw (2003) results compared gymnasts and non-gymnasts and showed that gymnasts are exposed to higher ground reaction forces than recreational athletes from other jumping sports (basketball and volleyball) when comparing the same task. These differences may occur because gymnasts are constantly exposed to repetitive high loads during landings in practice or competition that may jeopardize its performance and contributing to a major injury risk. In fact, this consequent exposure to repetitive landings should have contributed to their improvement, otherwise this study reports the opposite. Perhaps this phenomenon happens due to the lack of strength training/specific training for landings, cushioning capacity of gymnasts, lack of investment from coaches or even training in different surfaces. Since the musculoskeletal stiffness

regulates the storage and reuse of this elastic energy and gymnasts modulate total body stiffness in response to different landing conditions, training prepares gymnasts to perform the elements, including the landing phase (Leite et al., 2023).

Glynn et al. (2022) results showed that injured and non-injured gymnasts had inter-limb asymmetry. These data highlighted a common asymmetry of landing forces (no statistical differences for landing force and asymmetry of landing force when comparing injured and non-injured gymnasts). This information leads to conclude that in general gymnasts have a preference in their lower limbs which translates to common asymmetry in landings and anything or few has to deal with athlete's ankle injury.

There is not enough evidence to support that evaluating inter-limb asymmetry or magnitude is sufficient to examine ankle injury risks. Research about this topic in the upcoming years should consider other outcome measures to evaluate landing performance and injury risk and have a different complete task selection to fulfil these goals.

These high impacts experienced by gymnasts raises many concerns about repetitive stress injuries. Instruction in landing technique has been shown to reduce landing impact loads in child and adolescent recreational athletes and gymnasts (McNair & Prapavessis, 1999). High-impact loads may be reduced if gymnasts and athletes in general, are instructed and trained in landing technique, thereby minimizing the injury risk from repetitive high vertical-impact forces on the lower extremity.

4.2 Detailed image analysis

Detailed image analysis provides tools to analyze gymnastics elements in its smallest details and common errors. According to Cuk and Marinšek (2013), kinematic data was used to have proper measurement of the temporal and dynamic characteristics of the analyzed landings.

Both samples of the two reviewed studies used Junior and Senior athletes, members of MAG national teams from Slovenia (Cuk & Marinšek, 2013) and

Japan (Mizutori et al., 2021). The high level and high experience in gymnastics (Mizutori et al., 2021) reported as a mandatory minimum of 10 years of competitive gymnastics experience) guaranteed that the gymnasts were capable to demonstrate proficiency in the gymnastics skills performed. However, Mizutori et al. (2021) included less-skilled gymnasts with less years and level of practice, to be able to compare kinematics and joint movement profiles in different skill level gymnasts.

Mizutori et al. (2021) data results showed that larger shoulder flexion moments were observed in less- skilled compared with highly- skilled performers, while larger hip flexion moments were observed in straight arm press to handstand (SAPH). Since SAPH is an element that requires good balance rather than muscle strength itself (Mizutori et al., 2021), athletes with more experience are more capable of performing the correct technique of this element because they are able to put their center of mass below their back and shoulders, performing SAPH without the use of excessive muscle strength.

According to Kochanowicz et al. (2019) comparing different levels of performance analysis of the relationship between joint moments and moment profiles would enable the assessment of the performer's ability to coordinate moment patterns, e.g. neural control, and their level of skill.

Evaluating a gymnast's ability to coordinate moment patterns of movement is imperative to the development of a "highly-skilled" performer (Mizutori et al., 2021). For that reason, coaches play an important role to implement training methods to improve gymnast ability to coordinate joint moment patterns during its exercise's movements.

Regarding the procedure used, both articles analyzed specific gymnastics movements, which provided particular information about the sport itself and the concrete implications that these movements (performed correctly or with mistakes) have in practice. However, Cuk and Marinšek (2013) major focus was the influence of the symmetry/asymmetry of the acrobatic movements on the landing quality.

The average deduction for landing, calculated by Cuk and Marinšek (2013), was 0.30 points, which can be described as an average error according to FIG code of points. All the predictors under analysis defined asymmetries between the gymnast's lower limbs regarding different speeds and angles.

According to Cuk and Marinšek (2013), correct landings can be performed and they are in fact performed at competitions; from a motor control perspective it is easier to control the landing after a better performed element. This "perfection" relies on elements with optimum angular momentum, higher duration of flight and optimum angular momentum. In fact, to avoid asymmetric landings, gymnasts need to develop enough height, greater angular momentum around the transverse and longitudinal axis, and need to improve angular velocity in the longitudinal axis.

When analyzing these data, we conclude that this lack of symmetry has to be the subject of a lot of practical work that has to be enhanced by coaches in order to guarantee that young gymnasts learn to perform every landing as symmetrical as possible (Cuk & Marinšek, 2013).

4.3 Electromyography, force plates and detailed image analysis

Besides the use of separate research methods, the combination of EMG, force plates and detailed image analysis provides us with a much more in-depth analysis of gymnastics movements.

Considering the five articles described in the table 3, only two used case studies (Mills et al., 2008; C. L. Wu et al., 2019) which means that these researches results cannot lead to generalizations or be extended to other athletes since they concern to only one athlete with his own specific characteristics. Some authors choose to include in its samples only Elite level gymnasts to guarantee a higher level of proficiency of the analyzed exercises (Król et al., 2020; Mills et al., 2008; C. Wu et al., 2019; C. L. Wu et al., 2019). Two of them also referred the athlete's injury incidence in the 6 months prior to the evaluation (C. Wu et al., 2019; C. L.

Wu et al., 2019), which shows the concern for the gymnast's musculoskeletal health in the analysis.

When comparing gymnasts with age-matched non-athletes, gymnasts achieved 13% higher values of relative peak ground reaction forces in comparison with controls (Niespodziński et al. 2021). During long-term training, gymnasts exhibit different patterns of neuromuscular coordination aiming to implement safety and well performed landings to match the code of points. Authors like Horita et al. (2002) provided information about used strategies, showing that in gymnastics proper and safer landings were characterized by muscle activation and consequent contraction just before the moment of touchdown. In this study, younger gymnasts, aged 8 to 10 years, who have a higher rate of development, had the highest relative peaks of GRFs, due to their lack of experience and body control compared to older athletes. During the training of gymnastics routines, landings are repeated many times. Gymnasts are naturally exposed to a high frequency of impact landings and may be required to perform dismounts in excess of *200 times a week* (M. J. R. Gittoes & G. Irwin, 2012). These factors, associated with the gymnast younger age, can lead to musculoskeletal system overload and therefore to an increased risk of common injuries in gymnastic sports (Campbell et al., 2019).

To guarantee safer landings and the correct development of gymnasts it is important that training routines are suitable for the different stages of training and is also necessary that coaches monitor the technique and landings strategies but also the specific landing load if necessary.

Four studies analyzed specific gymnasts' movements in its analysis (Król et al., 2020; Mills et al., 2008; C. Wu et al., 2019; C. L. Wu et al., 2019) such as backward somersaults, forward rotating and backward rotating vaults, and only one analyzed a general exercise (Niespodziński et al., 2021), namely the countermovement jump.

C. L. Wu et al. (2019) data showed that gymnasts exhibited a different inter-limb symmetry in kinematics, kinetics and EMGs during the landing. This happened

because during the entire landing impact phase, the inter-limb difference between flexions of both hip and knee joints was within 5 degrees, and the difference in ankle dorsiflexion was within 10 degrees. Furthermore, the absolute symmetry index (ASI) of flexion in lower limb joints were less than 10% which showed an excellent landing symmetry in sports performance.

It was said before that good landing inter-limb symmetry in gymnasts is likely due to the equal distribution of load among the lower limbs (Sabick et al., 2006). However, according to C. L. Wu et al., (2019) the internal load experienced in lower limb joints can efficiently modulate the landing symmetry. Therefore, a symmetrical landing could be best accomplished by controlling several crucial factors such as lower limb kinetics and EMGs including GRF, torque, stiffness, power and eccentric work of multi-joints and synergy of antagonist and agonist muscles.

Another study conducted by the same author (C. Wu et al., 2019) quantified the lower extremity muscle activation of international-level gymnasts during BS landings. The conclusions of this research were that gymnasts first extend their lower extremity joints to increase the moment of inertia, and also for better reducing the body's angular velocity before landing. The lower extremity joints flex actively just before touchdown, continue flexing actively and rapidly in the initial impact phase, and then extend to resist the impact force and maintain body posture during the landing terminal impact phase.

There are many articles that describe what happens after the moment of ground contact in a landing such as M. J. R. Gittoes and G. Irwin (2012), C. L. Wu et al. (2019), Glynn et al. (2022), Sabick et al. (2006) and Niespodziński et al. (2021) but there is a lack of knowledge about the preparation and torque of the joints in the pre-landing phase (Verniba et al., 2017).

Chris Mills et al. (2008) also paid attention to the muscle activation profiles of co-contraction prior to landing. In fact, they revealed fairly high. As there were already high activation levels, the eccentric muscle forces were immediately large, but the concentric forces rapidly fell because the muscles were shortening

rapidly. This gave a rapid rise in the net extensor torque necessary to control the landing.

Strategies used by gymnasts as the ones reported by C. Wu et al. (2019) and Mills et al. (2008), such as gymnasts lower extremity joints flex continuously and actively, while increasing the activity levels of the lower extremity muscles must be taught by coaches and used by gymnasts to quickly absorb the impact and prevent injuries during the landing first moments. Król et al. (2020) for instance compared different movements in order to investigate the relationships between the internal and external structure of these jumps and concluded that the CMJ showed the highest level of vertical impulse, velocity, and displacement followed by the tucked backward somersault (TS), piked backward somersault (PS), and backward handspring (Ebben et al.). This ranking is made according to the force distance to the center of mass (Kerr et al.) meaning that for better performance of acrobatic jumps, it is necessary that the force vector must be transmitted vertically and, ideally, close to the COM. (Król et al., 2020). For that reason, when initiating an acrobatic jump coaches must carefully monitor the position of a gymnast's shoulders. Leaning backwards during the take-off while performing a standing backward acrobatic jump with rotation should be avoided (Król et al., 2020).

4.4 Different methods

Different methods are being used to study GRF and the biomechanics of gymnastics elements, that doesn't fit in any of the previous categories (Kirialanis et al., 2003; Mills et al., 2009; Mills et al., 2010; Rohleder & Vogt, 2019; Sonvico et al., 2019).

Data from the analyzed studies showed that not only gymnasts were evaluated in its procedures but also wobbling mass models of gymnasts as well. In Mills et al. (2009) and Mills et al. (2010) these models were chosen instead of humans because they are pretty accurate in terms of calculating bending moments, and because this is a simple method to determine the magnitude of the loading on

the skeletal structure and can be related to the fracture failure of bones from in-vitro tests. Also, with this analysis, authors are able to determine proper landing strategies without submitting gymnasts to GRF and internal forces.

The remaining three studies have large samples with high performance gymnasts competing in international championships, which ensures more experience in the sport, and so a guaranteed proficiency in the elements that were being evaluated.

Rohleder and Vogt (2019) examined floor exercise finals at the World Championships in 2013 (WC13), 2015 (WC15) and 2017 (WC17) using video analysis and official judges scores. These data provided evidence that current changes in world elite floor exercise gymnasts are characterized by generally decreased score levels due to rule changes according to the code of points 2017-2020 which said that landings must stick to have full punctuation on the landing movement.

These data provide a baseline for asymptomatic lumbar spine movements in an elite gymnastics population and provides insight into upper and lower lumbar spine movement during a simulated landing task. Stick landings during a floor routine is particularly recommended, but, with the current tendencies of increasing difficulties when composing floor exercise routines, gymnasts commit more errors during their routines, avoiding them to achieve better final scores. For this specific reason landing technique practice should be much more enhanced by coaches during trainings. During 1999-2000 season gymnasts observed by Kirialanis et al. (2003) had a total of 151 injuries reported for the 12-month experimental period; 93 (61.6%) were acute injuries and 58 (38.4%) overuse syndromes. The rate of mild injuries was 26.8% (25 cases), that of moderate injuries was 44% (41 cases) and that of major injuries was 29% (27 cases) (there was no significant difference between them). The authors also conclude that acute injuries occur much more often during floor exercises in both sexes, which could be expected since more time is spent in these event exercises as it is reported by Caine et al. (1989). The large load placed on lower limbs during landings, especially ankles and knees explains this high incidence of

injuries. These findings are worrying and should be considered by coaches and sports medicine personnel involved in developing and implementing injury prevention programs directed to gymnasts (Kiralanis et al., 2003).

When comparing real values to a simulation, C. Mills et al. (2009) data showed us that the successful minimization of GRF during landing led to higher internal loading than the matching simulation. Minimizing internal bone bending moments gave low peak GRF with an initial time history that looked much more similar to the matching performance, which may indicate the gymnast was trying to minimize internal loading. In this case, where the gymnast appears to perform a landing that is close to optimal with regards to internal loading, altering their landing to reduce GRF and mitigate injury risk would have had the opposite effect.

One year later, the same author showed that the optimization of six landing mat parameters for the forward and backward rotating vault resulted in the peak ground reaction forces being reduced, whilst the gymnast model maintained an acceptable landing technique according to the F.I.G. criteria (Mills et al., 2010). The stiffness of the current competition landing mat is optimum and a 20 % change in landing mat damping results in only a small reduction in internal forces within the gymnast. However, a large increase in damping would be of benefit and possibly reduce injury risk associated with vault landing in gymnastics. Increased mat damping may be associated with increased forefoot loading.

4.5 Limitations

One of the limitations of this systematic review is that it only includes studies from 4 databases, thereby potentially missing out other relevant publications in other platforms. A second limitation is having authors that published different papers about the theme that could have discorded in some of their conclusions becoming redundant in some topics. Furthermore, adding more experts to help in the quality control of the studies would be helpful in order to improve the accuracy of the analyzed papers. During this process it was clear that most of the research is still

skill oriented and that there are not much general approaches to performance training.

5 CONCLUSION

Research in artistic gymnastics took the first steps with published studies dating back to the mid-1820s, but there has been continued growing interest and increased research since 1920, with about 8000 studies published after this date.

Impacts on the ground and their respective reaction forces also became major research topics, mainly in athletes of a highly competitive level, with a high weekly training volume, since it was assumed that the high number of successive landings from gymnastics elements with high joint impact could lead to limbs overload and a decrease in the gymnast's performance.

The studies reviewed in our study allowed the identification of the most frequently procedure used in this research area: (1) studies using only force plates; (2) studies using detailed image analysis; (3) studies using EMG, force plates and detailed image analysis; and (4) studies using different methods. The most frequently addressed topics: (1) injury risk; (2) movement patterns; (3) landing strategies; (4) common errors on the execution of the elements; (5) material parameters.

The injury risk associated with landings in gymnastics is consensual by different authors in their research. This review showed us that gymnasts expose themselves to higher ground reaction forces than recreational athletes from other jumping sports (like basketball and volleyball) when comparing the same task (Seegmiller & McCaw, 2003), which raises concerns for repetitive stress injuries in gymnast because of high-impact loading. With this research we can conclude that landings performed by the gymnasts can lead to 2 different types of injuries: the most common - acute injuries, which occur in the landing moment due to trauma, such as a sprain, dislocation or fractures and chronic injuries, which are the least common but with 38.4% of incidence. According to Kirialanis et al.

(2003) "overuse" injuries, occur mainly due to repeated efforts, in this case the continuous repetition of landings with massive loads involved.

The reviewed literature emphasized different movement patterns during artistic gymnastics landings, but elements of different apparatus may have similar moment patterns, such as *round-off* phase of the *Yurchenko vault* and the floor exercise *round-off* (Seegmiller & McCaw, 2003). One example of this major differences in movement patterns was observed between highly skilled and less-skilled performers in hip joint moment production by Mizutori et al. (2021). During many years of practice and long-term training, gymnasts exhibit different patterns of neuromuscular coordination aimed to implement both safe and well performed landings according to the gymnastic rules.

What concerns to the landing strategies, there are notable differences between men and women and between athletes with more or less years of practice and level of training. Is consensual that men and women have different landing strategies, which led to differences in the sagittal range of motion at the knees and hips, with the men's landing strategy eliciting a larger range of motion decelerating the body upon impact (Straker et al., 2022). In fact, the existing literature indicates an individually favored landing strategy to meet informational constraints and therefore support the use of a single subject design. Therefore, we conclude that regardless of the extrinsic factors already mentioned above, gymnasts have an individual task response.

Landings in gymnastics are often performed with errors, minimal or on a large scale, which can then lead to the appearance of injuries derived from them. The main errors described in the literature are the inter-limb asymmetries, insufficient elements height, insufficient hip flexion and poor muscular pre-activation before the moment of contact with the ground.

In addition to gymnastic errors that affect the landings success, authors such as C. Mills et al. (2010) highlighted the influence that mattress characteristics have on this process, for example increased mat damping may be associated with increased forefoot loading. These subject specific findings provide a starting point

for future investigation and may have implications for future mat construction, possible modifications to gymnastics equipment regulations and the possibility of reducing the gymnasts' injury risk.

Finally, there is a need for more research about landing successful aspects impacting talent development in gymnastics and future strategies to be implement in practice by coaches that have a proper theoretical support base. It is essential that strength, physical preparation and specific landing training are worked rigorously and with the proper attention in practice. Investment in collaborations between clubs and laboratories is also a fundamental tool to promote more regular assessments, regarding the well-being of gymnasts.

4. Article 2

ARTICLE 2

WHAT IS THE INFLUENCE OF SPECIFIC PHYSICAL PREPARATION TRAINING IN REDUCING THE IMPACT OF LANDINGS IN ARTISTIC GYMNASTICS ELEMENTS?

Abstract: *The present study investigates the effects of a 6-week specific physical preparation protocol on landing impacts in artistic gymnastics elements. A total of 8 Junior and Senior male (Kara et al., 2023) and female (Mizutori et al., 2021) gymnasts from two elite gymnastics clubs in northern Portugal participated. Gymnasts were divided into an intervention group (IG) and a control group (Page et al.), with the IG completing a specific physical preparation program designed to improve landing mechanics, while the CG followed standard training. Gymnasts were evaluated before and after the intervention on six gymnastics floor elements—extension jump (EJ), half turn (HT), full turn (FT), front somersault (FS), back somersault (BS), and countermovement jump (CMJ) using force platforms to measure ground reaction forces, surface electromyography (EMG) to measure muscle activity and Biodex to measure isokinetical forces. The intervention, delivered three times a week over six weeks, incorporating coordination, strength, and mobility training aimed to improving control during landings. Results from force platform, EMG, and Biodex will quantify the effects of the intervention on landing impact forces and muscle activation patterns. This study addresses gaps in the literature by specifically targeting the unique demands of gymnastics landings and evaluating the efficacy of a targeted intervention in high-level athletes. Initial findings indicate a significant reduction in peak landing forces and an increase in muscle pre-activation levels, suggesting improved neuromuscular control during the landing phase. Moreover, the program demonstrated enhancements in vertical force absorption and torque production, reinforcing its potential for injury prevention and performance optimization in artistic gymnastics.*

Keywords: *Artistic gymnastics, Landing impact, Force platforms, Electromyography, Physical preparation*

1 INTRODUCTION

Landings are a technical movement present in every gymnastics exercise whether men's or women's gymnastics. Landings that involve controlled rotation and high-velocity impacts during floor contact are performed many times in this sport either they come from a vertical jump or from a dismount in a specific apparatus. Gymnasts are naturally exposed to a high frequency of impact landings and may be required to perform dismounts in excess of 200 times a week (Ozgüven & Berme, 1988). Since in the existing literature it is described that landings have a very low success rate in competition like it is showed in Prassas and Gianikellis (2002) and Marinsek (2010), coaches must be doated with strategies to implement in their practice to turn these landings into safer movements.

Physical preparation refers to the gymnast's ability to cope with the load to which they are exposed during elements in different apparatus (Marinsek, 2010) and is often associated with the success of the landings. For a gymnast, to perform safe landings he/she must be physically prepared to overcome the loadings at landings. One specific example of the importance of physical preparation is that when higher pre-activation happens (that is the activation of the muscles prior to touchdown), enables gymnasts to actively absorb energy and lower the loading on the heel (Verniba et al., 2017). Therefore, during training coaches must plan conditioning exercises that develop upper and lower body strength, and core stability and also exercises that emphasize learning and practicing correct landing techniques (Marinsek, 2010). Specific physical preparation's main goals rely on the improvement of technique, strength and spatial awareness of the elements of the sport. Gymnastics provides almost limitless possibilities for the study of human motion (Prassas et al., 2006), and for that reason further investigation happens about different topics of this sport.

Based on these facts and our active years of practice as Gymnasts and Coaches, with this research we intend to understand how we can reduce the impact of successive repetitions of landings, aiming to increase gymnasts' performance

and well-being. We will study Junior and Senior artistic gymnastics athletes, both man and women, from the 2nd, 1st division and Elites, from two clubs from North of Portugal, with the aim of understanding how technique training and specific physical preparation can increase technical quality of these movements, reduce or not their failure rate and the impacts (ground reaction forces) experienced by gymnasts when performing artistic gymnastics elements.

The main goals of this study consist in understanding the influence of a specific 6-week landing on the ground training protocol in Women Artistic Gymnastics (Mizutori et al., 2021) and Men Artistic Gymnastics (Kara et al., 2023) high-performance athletes. These objectives are divided into 3 specific objectives that we intend to see answered at the end of the research:

- Analyze the influence of a specific landing training protocol on the EMG activity of the muscles: Medial Gastrocnemius (GM), Lateral Gastrocnemius (GL), Peroneus Longus (PL) and Tibialis Anterior (TA) in the pre-activation and impact on the ground phases in artistic gymnastics elements.

- Analyze the influence of a specific landing training protocol on ground reaction forces in artistic gymnastics elements.

- Analyze the influence of a specific landing training protocol on knee flexion/extension, dorsi-flexion/plantar and foot inversion/eversion exercises using a isokinetic dynamometric protocol.

2 METHODOLOGY

2.1 Sample characterization

This research consists in an intervention study with an evaluation of several gymnastics elements landings before and after a 6-week protocol of specific physical preparation.

Our sample is a convenience sample, where Junior and Senior gymnasts of both sexes from the 1st and 2nd division and Elites from two gymnastics clubs in the

North of Portugal will be evaluated. The following sample inclusion criteria were established: (1) all gymnasts practice 6 times a week with a minimum training duration of 2 hours and 30 minutes; (2) enrollment at the clubs participating in the study; (3) absence of injury that prevented them from training in the last 3 months, during the intervention and at the time of evaluation and (4) attendance at a minimum of 80% of training sessions. Our sample was composed of 2 MAG from one gymnastics club from the north region of Portugal and 2 WAG athletes and 4 MAG athletes from another gymnastics club from the north region of Portugal. The sample will be divided into two randomized groups with same level gymnasts and with the same age group; an intervention group (IG), which will carry out the proposed specific physical preparation program and a control group (Page et al.) that will not carry out the program. Both groups had a similar training volume. The groups did not have the same number of subjects because 2 athletes from the IG were selected for European Championships which condoned their availability to participate in the study and 1 athlete from the CG got injured during the protocol time, which led to their exclusion from the sample. The sample size was restricted to the number of high-level gymnasts that could perform the movements that were going to be evaluated and that accepted and approved to carry out this study.

We used the statistical program G-Power, where we applied an effect size referenced in the literature of 0.8 by Brydges (2019) to calculate the necessary sample size. Thus, we reached a sample size of 26, considering a significance level of 0.05 and a power of 0.80. Gathering a sample size of this magnitude became extremely challenging and unmanageable due to the limited number of high-performance athletes in the sport in Portugal, and their geographic distribution being incompatible with our research, so we ended up with a total sample of 8 subjects.

Table 1

Sample characterization

Athletes	Gender	Age (years)	Hight (m)	Mass (Kg)	Dominant leg	Competitive level	Weekly training hours	Years of practice
1	Female	16	1,57	46,0	Right	2 nd Division	15	9
2	Female	16	1,55	48,50	Left	2 nd Division	15	12
3	Male	15	1,47	44,0	Left	Elite	17	8
4	Male	20	1,76	73,50	Left	Elite	17,5	13
5	Male	19	1,61	70,00	Left	Elite	17,5	11
6	Male	17	1,65	72,00	Right	1 st Division	17	9
7	Male	14	1,49	45,0	Right	1 st Division	15	8
8	Male	16	1,58	60,00	Right	1 st Division	17	7
M ± SD		16.6 ± 1.8	1.585 ± 0.086	57.38 ± 12.15			16.38 ± 1.08	9.63 ± 2.13

Mean (M), Standard deviation (SD)

2.2 Experimental setup and procedure

All ethical procedures were carried out following the Declaration of Helsinki, and the study was approved by the Ethical Committee of the Faculty of Sports of the University of Porto CEFAD 13 2023. All participants and their guardians (gymnasts aged under 18 years) were informed of the benefits and risks of the research. Before the beginning of the study, all the intervenients signed an informed consent document for testing, implementation of the training protocol, and publication of collected data. Evaluations were carried out at Porto University Biomechanics Laboratory (Labiomep).

Regarding the procedure itself and methodology, gymnasts were evaluated in the execution of 6 gymnastic floor elements. All the exercises guaranteed the performance of landings with rotations of the body in all possible axes, which are: (1) extension jump (EJ), (2) half turn (HT), (3) full turn (FT), (4) front somersault (FS), (5) back somersault (BS) and (6) countermovement jump (CMJ). The backward or forward rotation of a gymnast prior to the landing can affect the chosen landing strategy (Mills et al., 2008). The elements were evaluated exclusively on the floor since we have greater capacity to analyze impacts using force platforms and EMG that would be much more difficult in the remaining apparatus of artistic gymnastics.

The initial assessment took place after prior training familiarization, before the application of the specific physical preparation intervention program. After the

same intervention program there was an assessment with the same jumps evaluated in the first phase as well as a new familiarization with the elements under analysis.

Gymnasts' landings were evaluated using a set of three Bertec platforms. Two FP4060-15 platforms (40 x 60 x 15 cm) and one FP9060-15 platforms (90 x 60 x 15 cm), with a 12 inches mattress above them, to measure the three-dimensional ground reaction forces that act on the body during the selected exercises and an official Gymnova trampoline to perform the jumps prior to the landing. The mattress is similar to the ones used in training and official competitions and based on evidence from previously published studies regarding mattress thickness (Cuk & Marinšek, 2013; Mizutori et al., 2021; C. Wu et al., 2019).



Figure 1 and 2: Study setup with trampoline, mattress and force platforms underneath

In a synchronous and simultaneous way, force plates measurement and EMG of the muscles MG, LG, PL and TA using the Delsys Trigno Wireless system, was done.

During the test and after accommodation and warmup, the gymnasts used an isokinetic dynamometer, a device used to measure muscle strength under constant velocity conditions. The main goal of this evaluation was to measure

muscle strength while maintaining the speed of the movement controlled and constant, regardless of the force applied by the individual, and to verify whether or not there were strength gains from the beginning to the end of the protocol in the muscles highlighted for analysis. The gymnasts performed 3 tests: leg flexion and extension, foot inversion and eversion, dorsiflexion and plantar flexion of the foot, all with dynamic (isokinetic) and isometric evaluation. This process also served to control the isometric Maximal Voluntary Contraction (MVC) of each individual, which would later be used for electromyographic data normalization.

These were the three methods that we selected for evaluation since electromyography EMG allows us to understand which muscular chains are the most required in landings, force platforms allow us to quantitatively evaluate the ground reaction forces that each landing produces and Isokinetic dynamometer measures muscle strength and performance at a constant movement velocity and pre and post intervention phases.



Figure 3: Visual 3D motion capture analysis of athletes jumps and landings

The experimental procedure

After arriving at the laboratory, all the athletes were measured and weighed, and asked about their dominant leg in the sport. Following this, after explaining the procedures to which the participants would be subjected, subjects began a specific warm-up, as close to their usual routine as possible, to ensure they were in the best state of readiness and safety for the exercises they were about to perform. After the joint mobility warm-up and multi-jumps commonly used in gymnastics and before electrode placement, the skin surface was vigorously scrubbed with an alcohol swab. The surface electrodes were placed 2 cm apart

over the motor activation points of the MG, LG, PL and TA in accordance with European Recommendations for Surface Electromyography – SENIAM (Hermens et al., 2000) and secured with athletic tape. All electrodes were placed on both sides of the gymnast's body. All electrodes remained in place until the end of all trials. Cables from the electrodes to the transmitter were secured to the gymnast with athletic tape to minimize distraction to the gymnast and interference to the EMG signal.

Isometric MVC was measured in each gymnast, which would later be used for electromyographic data normalization. The MVCs were performed under isometric conditions on an isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA). In the procedure, the focus was set on the muscle groups that would be recruited in the following performed landings. The participant's pelvis was stabilized using leather straps and the shank and knee were supported by a leather bracket (Kochanowicz et al., 2019). Participants performed 3 isometric tests: leg flexion and extension, foot inversion and eversion, dorsiflexion and plantar flexion of the foot. In each position, participants performed three 4 seconds repetitions, with verbal encouragement to maximize their effort. The 4 seconds duration of the MVC was chosen as a compromise between 3 and 5 seconds used by other researchers (Niespodziński et al., 2021). There were 1 minute rest intervals between repetitions to reduce the effects of fatigue. After the isometric tests, participants performed the isokinetic dynamic tests with the following order leg flexion and extension, foot inversion and eversion, dorsiflexion and plantar flexion of the foot with the velocity of 60 degrees/second in each one.

In all tests, 5 consecutive repetitions of both movements were performed. Only the second, third, and fourth repetitions were included in the data analysis, as it is described in various literature on this type of protocol that the first repetition serves as an acclimation to the stimulus, and the last repetition is already affected by greater fatigue or reduced effort from the participant (Cools et al., 2007).

After the isokinetic tests were completed, the gymnasts were evaluated in their jumps at the force platforms by the following order: (1) countermovement jump,

(2) extension jump, (3) half turn, (4) full turn, (5) front somersault, and (6) back somersault. Before the actual evaluation, gymnasts had the opportunity to perform 2 jumps onto the mats in each exercise to become familiar with the exercise and the conditions of the mat and trampoline. All jumps were initiated from a stationary upright posture and with an arm swing. The order of the jumps was randomized, and 2-3 min rest intervals were allowed between subsequent trials. Each gymnast performed three CMJs on a force plate. This approach allowed considering the individual potential in the context of the development of landing control mechanisms (Rohleder & Vogt, 2019). The remaining exercises were performed with a minimum of 3 and a maximum of 6 repetitions, and only the 3 static landings of the gymnasts, where there were no extra steps to dissipate energy, were considered to evaluation. In cases where there were not 3 landings without any additional steps, the 3 landings with the smallest additional steps were selected for analysis. After this selection, a group of artistic gymnastics technical experts, who are current judges for this Olympic cycle, evaluated the footage of these 3 jumps, selecting the best landing for each exercise.

2.3 Intervention program protocol

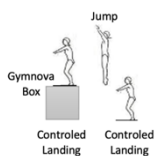
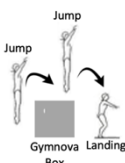
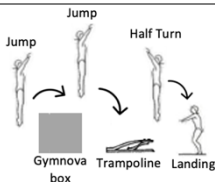
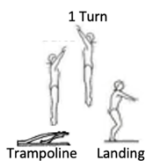
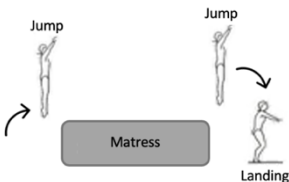
The intervention program consisted in a 6-week mesocycle of specific and technical physical preparation, including coordination work (control), strength and mobility aimed entirely on improving gymnastics elements landings on the floor. The protocol lasted about 15 minutes and was applied 3 times a week at the beginning of the training. Before this intervention gymnasts performed their general warm-up. The chosen protocol was carried out in a circuit with 5 stations with 2 gymnasts in each one, where the different types of rotations around the body axes, transversal and longitudinal, and the landings that result from them were deconstructed. This mesocycle lasted 6 weeks and had a load increase at the beginning of the 4th week of intervention, manipulating the height of the jump prior to landing and the external load attached to the gymnasts.

The protocol in the first 3 weeks; gymnasts begun the intervention program with a mobility exercise aimed at the soleus and gastrocnemius muscles with the aim of increasing joint range of motion and pre-activating these muscles, highly

recruited during landing (Król et al., 2020). Gymnasts then performed 4 FS and 4 BS starting from the floor with static landings. (Gymnasts write down in a table the number of successful landings: 1/4, 2/4, 3/4, 4/4 in all training sessions that comply with the protocol, as well as the noise of each landing using the app “Noise exposure.” After that the gymnasts started the circuit of exercises that is showed in the following table.

Table 2

Physical preparation circuit of exercises for the first 3 weeks of the protocol.

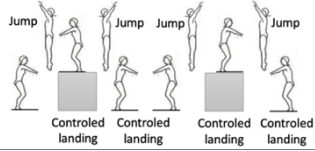
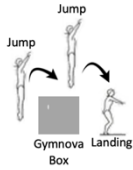
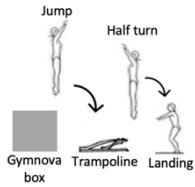
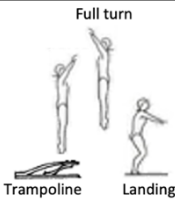
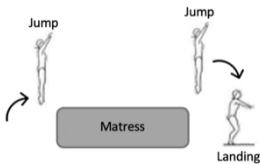
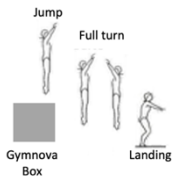
1		10X	Description: Jumps from the top of the Gymnova box (40 cm) to the floor and from the floor to the top of the Gymnova box with a controlled landing between each one.
2		5X	Description: Vertical jump onto the Gymnova box (40cm) followed by an extension jump with landing on the floor.
3		3X each side	Description: Vertical jump onto the Gymnova box (40cm) followed by a jump onto the trampoline, followed by an extension jump with ½ pirouette with landing on the floor.
4		10x	Description: 1 Pirouette starting from the trampoline and landing on the floor.
5		5x	Description: Vertical jump from the ground onto a mattress (height 60 cm) followed by a vertical jump with landing on the floor.

At the end of the circuit, gymnasts performed a strength exercise. Squat with a barbell with 25% of the gymnasts' weight in the first two weeks and the same exercise starting on the tip of the toes in the third week. In this way, in the third week there is an increase of coordination requirements, and the task becomes more complex.

Gymnasts finished the circuit by performing 4 FS and 4 BS starting from the floor with static landings. (Gymnasts wrote down in a table the number of successful receptions: 1/4, 2/4, 3/4, 4/4 in all training sessions that comply with the protocol, as well as the noise of each landing using the app "Noise exposure."). The protocol in the last 3 weeks; gymnasts begun the intervention program with a mobility exercise focused on the soleus and gastrocnemius muscles with the aim of increasing joint range of motion and pre-activating these muscles, highly recruited during landing (Król et al., 2020). Gymnasts then perform 4 FS and 4 BS starting from the floor with static landings. (Gymnasts write down in a table the number of successful landings: 1/4, 2/4, 3/4, 4/4 in all training sessions that comply with the protocol, as well as the noise of each reception using the app "Noise exposure.") After that the gymnasts started the circuit of exercises that is showed in table 3.

Table 3

Physical preparation circuit of exercises for the last 3 weeks of the protocol.

1		10x	Description: Jump to the box with rotation to the right, jump down with rotation to the right. Change the direction of the same exercise with left rotation.
2		5x	Description: Vertical jump onto the Gymnova box (60cm) followed by an extension jump with landing on the floor.
3		3x each side	Description: Vertical jump from the top of the Gymnova box (60cm) to the trampoline, followed by ½ pirouette with landing on the floor.
4		10x	Description: 1 Pirouette starting from the trampoline and landing on the floor.
5		5x	Description: Vertical jump from the ground onto a mattress (height 70 cm) followed by a vertical jump with landing on the floor.
6		3x each side	Description: Jump from the top of the Gymnova box (40 cm) to the floor followed by 1 pirouette with controlled landing.

At the end of the circuit, gymnasts performed a strength exercise. Squat with a barbell with 50% of the gymnasts' weight in the first two weeks and the same exercise starting on the tip of the toes in the third week. In this way, in the third week there was an increase of coordination requirements, and the task becomes

more complex. Gymnasts finished the circuit by performing 4 FS and 4 BS starting from the floor with static landings. (Gymnasts wrote down in a table the number of successful receptions: 1/4, 2/4, 3/4, 4/4 in all training sessions that comply with the protocol, as well as the noise of each landing using the app “Noise exposure.”)

In order to control the reliability and correct implementation of this protocol, considering that there may be possible absences from training sessions where this circuit took place, we have established that for the gymnasts to be able to participate in the final assessment, they had to participate in at least 90% of the training sessions where the circuit is completed.

All gymnasts included in our sample must already have all the elements that were going to be performed in the assessment acquired and be able to perform them proficiently before the intervention. This measure ensures not only greater safety for the athletes, but also greater focus on the effectiveness of the exercises that we included in our program. This mesocycle always had a coach observing all the process and giving feedback on the technical quality of the movements performed by the gymnasts. We also had a registration form for the control of the gymnasts themselves with the success criteria of their landings, which were: number of static receptions (without any foot movement) and lowest possible noise at the time of the landing with a scale of 1 to 3. This scale was created using the “noise exposure” app where the sound of each landing was captured by a phone or tablet (1 - GREEN ZONE of the app: less than 80 decibels when the feet hit the floor, damped landing, 2 - YELLOW ZONE of the app: between 80 and 90 decibels when the feet hit the floor, 3 - RED ZONE from the app: more than 90 decibels when the feet hit the floor).

2.4 Study Variables

When conducting an evaluation using an isokinetic dynamometer, several variables were considered to ensure a comprehensive and accurate analysis of muscle function. The main study variables include:

In Isometric evaluations:

- Peak Torque (Newton-Meters): highest muscular force output at any moment during a repetition. Indicative of a muscle's strength capabilities.
- Average peak torque/bodyweight (%): represented as a percentage normalized to bodyweight and compared to an established goal.
- Coefficient of variation (CV) (%): statistical representation of test validity based on reproducibility of performance. Lower values demonstrate higher reproducibility.
- Agonist/Antagonist ratio (%): the reciprocal muscle group ratio. Excessive imbalances may predispose a joint to injury.

In Isokinetic evaluations:

- Peak Torque (Newton-Meters): highest muscular force output at any moment during a repetition. Indicative of a muscle's strength capabilities.
- Average Peak Torque/bodyweight (%): represented as a percentage normalized to bodyweight and compared to an established goal.
- Coefficient of variation (%): statistical representation of test validity based on reproducibility of performance. Lower values demonstrate higher reproducibility.
- Agonist/Antagonist ratio (%): the reciprocal muscle group ratio. Excessive imbalances may predispose a joint to injury.
- Time to Peak Torque (TPT) (milliseconds): the amount of time it takes for a muscle to reach its maximum (or peak) torque during a contraction. This variable is critical for assessing muscle responsiveness and explosiveness, which are especially important in activities requiring rapid, powerful movements.

Force platform variables

- Peak Vertical Ground Reaction Force (vGRF) (Newtons): the maximum force exerted by the ground on the gymnast during landing, in the vertical direction.
- Horizontal Ground Reaction Force (hGRF) (Newtons): the ground reaction forces measured in the anterior-posterior and medial-lateral directions.

- Time to Peak Vertical Ground Reaction Force (TPvGRF) (milliseconds): the duration it takes for the vGRF to reach its maximum value during a landing.
- Impulse (Newton-Seconds): the integral of force over time during the landing, representing the total amount of force absorbed.

Analyzing EMG variables in gymnastics provides crucial insights into muscle function, performance optimization, and injury prevention. By understanding muscle activation patterns, coaches and athletes can refine training techniques and enhance overall performance in this demanding sport (Niespodziński et al., 2021).

Analysis Time: (0–100 ms) before contact (0–100 ms) after landing, and second period (100–200 ms) after contact (100–200 ms) (Niespodziński et al., 2021)

The variables that we chose to study were:

- Percentage of MVC $\pm$ standard deviation - 100 ms before landing: express the level of muscle activation as a percentage of the MVC just prior to landing.
- Percentage of MVC $\pm$ standard deviation - 0–100 ms after contact (%): assesses the muscle activation in the first 0–100 milliseconds after the gymnast contacts the ground. It shows how much force is generated relative to the MVC immediately following impact.
- Percentage of MVC $\pm$ standard deviation - 100–200 ms after contact (%): evaluates muscle activation during the 100–200 milliseconds after ground contact. It provides insight into the muscle's ability to stabilize and control the body during this critical time frame.
- Percentage of coactivation Antagonist–Agonist (GM, GL, PL, TA) (%): This refers to the coactivation of antagonist and agonist muscles during landing, specifically looking at muscle groups. Coactivation is the simultaneous activation of agonist, antagonist or synergist muscles surrounding a joint contract simultaneously to provide joint stability and

control during landing. This percentage indicates the balance of muscle activation between these groups and is important for understanding how effectively the body manages forces during dynamic movements. Regarding the muscles that we choose, Lateral/Medial Gastrocnemius and Tibialis Anterior are antagonists in plantar flexion/dorsiflexion and Peroneus Longus and Tibialis anterior are antagonists in eversion/inversion of the foot.

In table 4 we present the variables in analysis in each evaluation:

Table 4

Study variables

Isokinetic Dynamometry	Force platforms	Electromyography
Peak Torque (Newton-Meters)	Peak Vertical Ground Reaction Force (Newtons)	Percentage of MVC 100 ms before landing (%)
Coefficient of Variation (%)	Horizontal Ground Reaction Force (Newtons)	Percentage of MVC- 0–100 ms after floor contact (%)
Average Peak Torque/bodyweight (%)	Time to Peak Vertical Ground Reaction Force (Milliseconds)	Percentage of MVC - 100–200 ms after floor contact (%)
Agonist/Antagonist ratio (%)	Impulse (Newton-Seconds)	Percentage of coactivation Antagonist–Agonist (%)
Time to Peak Torque (Milliseconds)		

2.5 Statistical description and data analysis

Statistical procedures were performed using IBM SPSS Statistics software, version 27.0.1.0, for Macintosh.

Given the existing scenario, where there is a small sample (8 subjects), with a control group and an experimental group, and an evaluation before and after a 6-week intervention protocol, a non-parametric test was chosen due to the small sample size and the lack of normality in the data. The *Mann-Whitney U* test was used to compare the changes between the two groups (experimental and control)

in a non-parametric manner. This test was applied to compare two independent samples since the assumptions of normality were not met.

Since there are pre and post-intervention measurements within each group, it was also necessary to compare the internal differences (pre and post) within each group. The *Wilcoxon* test for paired samples was used to evaluate whether there was a significant difference between the pre- and post-intervention measurements within each group. The probability level accepted for statistical significance was $p \leq 0.05$.

3 RESULTS

The same arrangement of data processing was applied across all three tests performed by the participants in the force platform, isokinetic dynamometer, and surface EMG. After conducting an individual analysis of each parameter, we obtained the means and standard deviations for each of them, and then we estimated the p-value for each parameter (Table 5 and 6).

Table 5

Table of Force Platforms variable analysis – Control Group (Pre and post 6-week)

Variable	Moment 1 (Pre)	Moment 2 (Post)	Change	p-value
Peak Vertical GRF (vGRF) (N)	1200 ± 150	1235 ± 148	+35	0.16
Horizontal Ground Reaction Force (hGRF) (N)	400 ± 50	415 ± 52	+15	0.18
Time to Peak Vertical Ground Reaction Force (TPvGRF) (ms)	250 ± 30	245 ± 28	-5	0.22
Impulse (Ns)	350 ± 40	360 ± 42	+10	0.14

In table 6, regarding the variables from the experimental group we verified 2 p-values < 0.05, the peak vertical GRF and the time to peak vertical GRF.

Table 6

Table of Force Platforms variable analysis – Experimental Group (Pre and post 6-week Intervention)

Variable	Moment 1 (Pre)	Moment 2 (Post)	Change	p-value
Peak Vertical GRF (vGRF) (N)	1300 ± 160	1225 ± 150	-75	0.03*
Horizontal GRF (hGRF) (N)	420 ± 55	415 ± 53	-5	0.18
Time to Peak Vertical GRF (TPvGRF) (ms)	260 ± 32	265 ± 30	+5	0.04*
Impulse (Ns)	365 ± 45	360 ± 43	-5	0.20

The following table 7 compares the control group and the experimental group data to analyze if there are any differences between them. Peak Vertical GRF and Time to Peak Vertical GRF showed significant differences between groups, hGRF and Impulse did not show significant differences. These findings suggest that the experimental group experienced significant changes in vertical force and time to peak force, while the control group did not.

Table 7

Comparison between control and experimental Group – Force Platforms analysis

Variable	Control group (Δ= post - pre)	Experimental group (Δ= post - pre)	U (Mann-Whitney test)	p-value
Peak vertical GRF (N)	+35	-75	5.0	0.02*
Horizontal GRF N)	+15	-5	10.5	0.25
Time to peak vertical GRF(ms)	-5	+5	6.0	0.04*
Impulse (Ns)	+10	-5	9.0	0.18

*(Values with statistical significance)

The following tables shows isokinetic parameters. Table 8 present the parameters for the control group, pre- and post-6-week without intervention program.

Table 8

Table of Isokinetic variable analysis – Control Group (Pre and post 6-week Intervention)

Movement/variable	Moment 1 (pre)	Moment 2 (post)	Change	P-value
DORSIFLEXION / PLANTAR FLEXION				
Peak torque (Nm)	52.1 ± 6.5	53.2 ± 6.7	+1.1	0.69
Coefficient of variation (%)	6.5 ± 1.2	6.3 ± 1.1	-0.2	0.77
Avg. Peak torque/bodyweight (%)	30.4 ± 3.5	30.9 ± 3.7	+0.5	0.64
Agonist/antagonist ratio (%)	61.5 ± 5.0	61.8 ± 5.1	+0.3	0.81
Time to peak torque (ms)	280.1 ± 15.8	279.2 ± 14.9	-0.9	0.89
KNEE FLEXION / EXTENSION				
Peak torque (Nm)	145.7 ± 12.8	147.1 ± 13.1	+1.4	0.73
Coefficient of variation (%)	8.1 ± 1.4	8.0 ± 1.3	-0.1	0.83
Avg. Peak torque/bodyweight (%)	85.2 ± 8.5	85.9 ± 8.6	+0.7	0.61
Agonist/antagonist ratio (%)	58.4 ± 4.7	58.7 ± 4.6	+0.3	0.76
Time to peak torque (ms)	350.4 ± 22.1	349.5 ± 21.8	-0.9	0.87
INVERSION / EVERSION OF THE FOOT				
Peak torque (Nm)	37.5 ± 5.8	38.1 ± 5.7	+0.6	0.68
Coefficient of variation (%)	7.3 ± 1.1	7.2 ± 1.0	-0.1	0.82
Avg. Peak torque/bodyweight (%)	22.8 ± 2.9	23.2 ± 3.0	+0.4	0.74
Agonist/antagonist ratio (%)	65.7 ± 4.5	65.9 ± 4.3	+0.2	0.79
Time to peak torque (ms)	295.6 ± 18.4	294.9 ± 17.7	-0.7	0.90

Table 9 presents the experimental group, pre- and post-6-week intervention program. The table includes measures of Peak Torque (Nm), Coefficient of Variation (%), Average Peak Torque/Bodyweight (%), Agonist/Antagonist ratio (%), and Time to Peak Torque (ms). The effect of the condition on the different variables was verified and the p-value was always greater than 0.05, as shown the table 8. In Table 9, some variables show a p-value < 0.05, namely the Peak Torque and the Coefficient of Variation.

Table 9

Table of Isokinetic variable analysis – Experimental Group (Pre and post 6-week Intervention)

Movement/variable	Moment 1 (pre)	Moment 2 (post)	Change	P-value
DORSIFLEXION/PLANTAR FLEXION				
Peak torque (Nm)	55.0 ± 7.2	62.5 ± 7.9	+7.5	0.02*
Coefficient of variation (%)	9.0 ± 1.5	7.4 ± 1.3	-1.6	0.03*
Avg. Peak torque/bodyweight (%)	34.5 ± 3.8	36.0 ± 4.1	+1.5	0.12
Agonist/antagonist ratio (%)	61.5 ± 5.0	62.0 ± 4.8	+0.5	0.15
Time to peak torque (ms)	270.0 ± 19.5	268.2 ± 18.7	-1.8	0.18
KNEE FLEXION / EXTENSION				
Peak torque (Nm)	125.3 ± 10.6	135.7 ± 11.2	+10.4	0.03*
Coefficient of variation (%)	9.5 ± 1.8	8.0 ± 1.6	-1.5	0.04*
Avg. Peak torque/bodyweight (%)	67.2 ± 5.8	69.0 ± 6.1	+1.8	0.12
Agonist/antagonist ratio (%)	73.0 ± 4.2	73.5 ± 4.0	+0.5	0.15
Time to peak torque (ms)	340.0 ± 23.6	338.4 ± 21.9	-1.6	0.21
FOOT INVERSION / EVERSION				
Peak torque (Nm)	40.3 ± 5.9	45.1 ± 6.2	+4.8	0.03*
Coefficient of variation (%)	8.5 ± 1.6	7.0 ± 1.4	-1.5	0.04*
Avg. Peak torque/bodyweight (%)	28.6 ± 3.5	30.1 ± 3.7	+1.5	0.14
Agonist/antagonist ratio (%)	65.0 ± 4.8	65.4 ± 4.6	+0.4	0.16
Time to peak torque (ms)	290.0 ± 18.4	288.5 ± 17.8	-1.5	0.19

*(Values with statistical significance)

Table 10 shows the results of the Mann-Whitney U test that was used to compare the changes between the Control group and the Experimental group.

The Experimental group showed significant changes in Peak Torque, Coefficient of Variation, and Knee Flexion/Extension across all three movements (Dorsiflexion/Plantar Flexion, Knee Flexion/Extension, and Foot Inversion/Eversion). The Control group showed no significant changes across the variables.

Table 10

Comparison between control and experimental Group – Isokinetic analysis

Movement/variable	Control group (Δ = post - pre)	Experimental group (Δ = post -pre)	U (Mann- Whitney test)	P- value
DORSIFLEXION / PLANTAR FLEXION				
Peak torque (Nm)	+1.1	+7.5	10.0	0.02*
Coefficient of variation (%)	-0.2	-1.6	18.5	0.03*
Avg. Peak torque/bodyweight (%)	+0.5	+1.5	15.0	0.12
Agonist/antagonist ratio (%)	+0.3	+0.5	20.0	0.15
Time to peak torque (ms)	-0.9	-1.8	25.0	0.18
KNEE FLEXION / EXTENSION				
Peak torque (Nm)	+1.4	+10.4	9.5	0.03*
Coefficient of variation (%)	-0.1	-1.5	22.0	0.04*
Avg. Peak torque/bodyweight (%)	+0.7	+1.8	14.5	0.12
Agonist/antagonist ratio (%)	+0.3	+0.5	24.0	0.15
Time to peak torque (ms)	-0.9	-1.6	18.5	0.21
FOOT INVERSION / EVERSION				
Peak torque (Nm)	+0.6	+4.8	13.0	0.03*
Coefficient of variation (%)	-0.1	-1.5	20.0	0.04*
Avg. Peak torque/bodyweight (%)	+0.4	+1.5	14.5	0.14
Agonist/antagonist ratio (%)	+0.2	+0.4	21.0	0.16
Time to peak torque (ms)	-0.7	-1.5	19.0	0.19

*(Values with statistical significance)

The following tables present the results of the surface EMG variable analysis for the control group (Table 11) and the experimental group (Table 12). The variables analyzed were: percentage of MVC - 100 ms before landing, percentage of MVC - 0–100 ms after floor contact, percentage of MVC - 100–200ms after floor contact, and percentage of coactivation between antagonist–agonist muscles involved. The values reflect surface EMG measures from gymnasts in a control group where the intervention protocol did not result in significant changes (table 11).

Table 11

Table of surface EMG analysis – Control Group (Pre and post 6-week)

Variable	Moment 1 (Pre)	Moment 2 (Post)	Change	p-value
% of MVC $\pm$ SD - 100 ms before landing	80.5 $\pm$ 6.3	81.2 $\pm$ 6.4	+0.7 %	0.27
% of MVC $\pm$ SD - 0–100 ms after contact	95.4 $\pm$ 7.1	96.1 $\pm$ 7.2	+0.7 %	0.21
% of MVC $\pm$ SD - 100–200 ms after contact	85.7 $\pm$ 5.8	85.9 $\pm$ 6.0	+0.2 %	0.35
% of coactivation Antagonist–Agonist (MG, LG, PL, TA)	42.6 $\pm$ 4.9	42.1 $\pm$ 5.0	-0.5 %	0.19

Medial Gastrocnemius (MG), Lateral Gastrocnemius (LG), Peroneus Longus (PL), Tibialis Anterior (TA)

On table 12, the % of MVC 100 ms before landing: showed significant increase with a p-value < 0.05, such as % of MVC 0–100 ms after contact showed a p-value $\leq$ 0.05 and also % of MVC $\pm$ SD - 100–200 ms after contact - p $\leq$ 0.05 (p-significance level).

Table 12

Table of surface EMG analysis – Experimental Group (Pre and post 6-week Intervention)

Variable	Moment 1 (Pre)	Moment 2 (Post)	Change	p-value
% of MVC $\pm$ SD - 100 ms before landing	78.5 $\pm$ 6.2	85.3 $\pm$ 6.4	+6.8 %	0.02*
% of MVC $\pm$ SD - 0–100 ms after contact	92.3 $\pm$ 7.0	93.5 $\pm$ 6.9	+1.2 %	0.049*
% of MVC $\pm$ SD - 100–200 ms after contact	83.9 $\pm$ 5.7	84.8 $\pm$ 5.5	+0.9 %	0.044*
% of coactivation Antagonist–Agonist (GM, GL, PL, TA)	41.8 $\pm$ 4.8	42.0 $\pm$ 4.6	+0.2 %	13.63

Medial Gastrocnemius (MG), Lateral Gastrocnemius (LG), Peroneus Longus (PL), Tibialis Anterior (TA)

*(Values with statistical significance)

Table 13 shows the changes between the Control and Experimental Group. The Experimental Group showed significant improvements in % of maximal voluntary contraction in all time intervals (100 ms before landing, 0–100 ms after contact, and 100–200 ms after contact). The Control Group showed minimal or no significant changes across the variables, Coactivation (Antagonist–Agonist) did not show significant differences between the two groups.

Table 13

Comparison between control and experimental Group – surface EMG analysis

Variable	Control Group (Δ = Post - Pre)	Experimental Group (Δ = Post - Pre)	U (Mann- Whitney U Test)	P- Value
% Of MVC $\pm$ Sd - 100 Ms Before Landing	+0.7	+6.8	5.0	0.02*
% Of MVC $\pm$ Sd - 0–100 Ms After Contact	+0.7	+1.2	8.5	0.04*
% Of MVC $\pm$ Sd - 100– 200 Ms After Contact	+0.2	+0.9	9.0	0.05*
% Of Coactivation Antagonist–Agonist (Gm, Gl, Pl, Ta)	-0.5	+0.2	12.0	0.10

*(Values with statistical significance)

Figure 5 shows the variation of percentage of MVC over time since 100 ms before landing and 100-200 ms after floor contact (in milliseconds) for the four athletes from the experimental group. We opted to include this figure to present the information in a distinct format from the previously shown table. By visualizing a timeline, it becomes possible to more clearly and intuitively analyze the evolution of MVC over time.

The graph includes individual values for each athlete, and the dashed line represents the average, which matches the values provided in the earlier table (table 10).

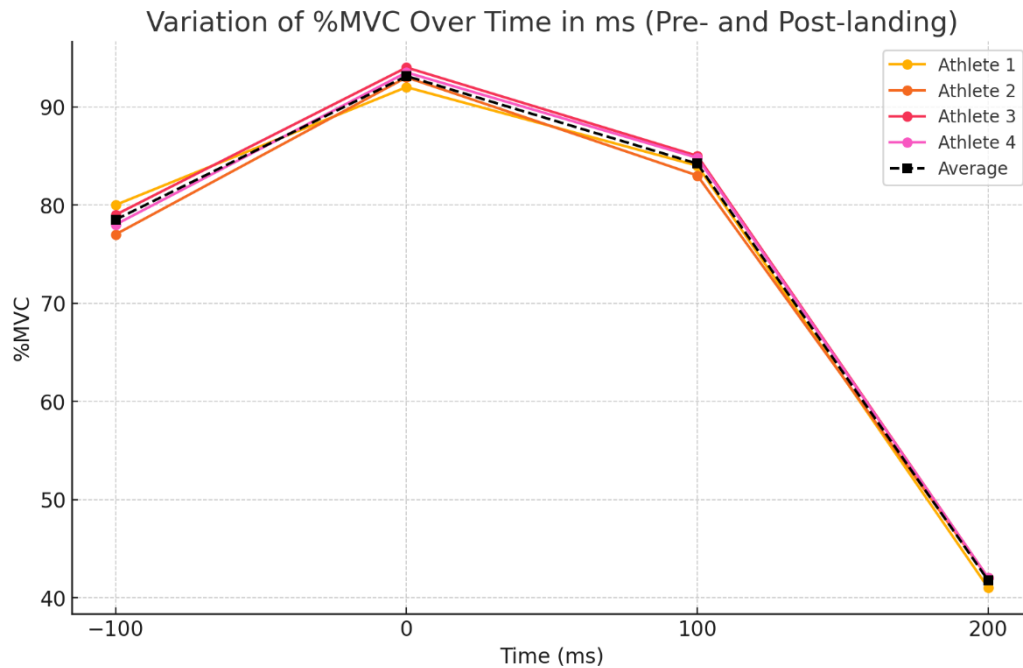


Figure 4: Graph representing the variation of %MVC over time in ms in the experimental group (pre- and post- landing)

4 DISCUSSION

The existing literature researched in our systematic review highlights significant differences in landing strategies between men and women, as well as among athletes with varying years of practice and training levels. It is widely accepted that men exhibit a landing strategy characterized by a greater sagittal range of motion at the knees and hips, which facilitates better deceleration upon impact (Straker et al., 2022). Furthermore, individual landing strategies are influenced by informational constraints, supporting the relevance of single-subject designs in research. Common errors identified in landing mechanics include inter-limb asymmetries, insufficient element height, inadequate hip flexion, and poor muscular pre-activation before ground contact (Mills et al., 2010). Given these biomechanical challenges, it is crucial to rigorously integrate strength training, physical conditioning, and specific landing drills into practice to optimize performance and reduce injury risk.

The findings of our experimental study complement this information by demonstrating that a six-week landing preparation protocol led to significant

reductions in vertical ground reaction forces and increased time to peak force in the experimental group. Specifically, the peak vertical GRF ($p = 0.03$) improved and the time to peak vertical GRF ($p = 0.04$) decreased significantly in the experimental group, whereas no significant changes were observed in the control group. These results suggest enhanced impact absorption and greater neuromuscular control during landings, in line with previous studies highlighting the role of neuromuscular training in mitigating landing forces (Verniba et al., 2017). RFD refers to the speed at which force is produced by the neuromuscular system, typically measured as the slope of the force-time curve during explosive muscle contractions (Aagaard et al. 2002). In this specific case, the observed increase in time to peak vertical GRF suggests a reduction in the RFD, indicating that participants in the experimental group generated force more gradually upon landing, taking more time to absorb all the energy that a specific landing required. While a lower RFD is often viewed as adverse in explosive tasks, in the context of landing mechanics, it may reflect a protective adaptation that enhances impact attenuation and joint stability by reducing abrupt loading (Andersen & Aagaard 2006). This controlled force application aligns with the goals of neuromuscular training interventions protocols aimed at minimizing injury risk through improved biomechanical efficiency and safer landing strategies.

Furthermore, the comparative analysis between the control and experimental groups revealed significant differences in key variables. While the control group exhibited non-significant increases in peak vertical GRF (35 N) and horizontal GRF (15 N), the experimental group experienced a notable reduction in peak vertical GRF (75 N) and an increase in time to peak force (5 ms). These differences, confirmed by the Mann-Whitney U test ($p = 0.02$ and $p = 0.04$, respectively), reinforce the effectiveness of the intervention in optimizing landing mechanics.

In addition to force plate analysis, isokinetic assessments further validated the benefits of the intervention. The experimental group showed significant improvements in peak torque for dorsiflexion/plantar flexion ($p = 0.02$), knee flexion/extension ($p = 0.03$), and foot inversion/eversion ($p = 0.03$). These

increases in strength, combined with a significant reduction in the coefficient of variation across all three movements, suggest improved muscular stability and control. In contrast, the control group showed no significant changes in any isokinetic parameters.

Surface EMG data reinforced these findings by revealing significant improvements in neuromuscular activation in the experimental group. Pre-activation muscle activity (100ms before landing) increased significantly ($p = 0.02$), along with muscle activation within the first 100ms post-landing ($p = 0.049$) and 100–200ms post-landing ($p = 0.044$). These results align with previous research emphasizing the importance of pre-activation and early post-landing muscle engagement in reducing impact forces and improving landing stability (Jones et al., 2016). Interestingly, the control group did not exhibit any significant changes in muscle activation patterns, highlighting the necessity of specific training interventions to enhance neuromuscular response during landings.

Another critical factor analyzed in our study was the variation in landing strategies based on individual differences, including gender and training level. Previous studies have reported that female gymnasts tend to adopt landing strategies that result in higher knee valgus and increased sagittal plane motion at the hips and knees, potentially increasing injury risk (Straker et al., 2022). Our findings suggest that personalized training approaches, such as those implemented in the experimental group, can help mitigate these risks by promoting improved neuromuscular control and force distribution during landings.

Overall, our results highlight the effectiveness of a targeted landing preparation protocol in reducing impact forces, improving strength parameters, and enhancing neuromuscular activation in artistic gymnasts. The significant improvements in the experimental group underscore the necessity of incorporating specialized training programs into gymnastics routines to minimize injury risks and optimize performance. Given the high demands of artistic gymnastics, future research should explore the long-term effects of such interventions and their potential benefits for gymnasts across different skill level.

Technical training of gymnastics elements, while essential for skill execution, does not fully equip gymnasts with the specific physical preparation required to optimize their landing performance. Effective landings rely not only on technical precision but also on adequate strength, mobility, and neuromuscular control to absorb impact efficiently and maintain stability. Therefore, incorporating a complementary training regimen that includes coordination work (control), strength development, and mobility training can play a crucial role in enhancing landing mechanics. By addressing these key physical components, gymnasts may significantly improve their ability to execute safer and more successful landings, ultimately contributing to overall performance.

5 CONCLUSIONS AND PRACTICAL IMPLICATIONS

The first objective of this study was to assess the impact of a six-week targeted landing preparation protocol on high-performance male and female artistic gymnasts. By focusing on three key biomechanical factors: muscle electromyographic activity, ground reaction forces during gymnastic elements, and isokinetic dynamometry measurements, this research aimed to provide a comprehensive understanding of how specialized training influences landing mechanics. Additionally, the study sought to analyze changes in neuromuscular activation, force absorption, and joint stability following the intervention, offering evidence-based recommendations for coaches and athletes to optimize landing safety and performance in Artistic Gymnastics.

The findings of this study demonstrated that a structured landing preparation protocol that includes coordination, strength and mobility training can improve impact absorption and neuromuscular control during landings. Specifically, the experimental group showed a significant reduction in peak vertical ground reaction force and an increase in time to peak force, indicating enhanced force dissipation and improved landing mechanics. Furthermore, the isokinetic dynamometry analysis revealed significant improvements in peak torque for dorsiflexion/plantar flexion, knee flexion/extension, and foot inversion/eversion.

These findings highlight the critical role of targeted muscle strengthening in enhancing joint stability and motor control during high-impact movements.

Surface EMG data further supported these findings, demonstrating significant increases in muscle activation before and after landing. The experimental group exhibited a significant improvement in pre-activation muscle activity (100ms before landing), as well as early post-landing activation (0–200ms). These results suggest that neuromuscular training effectively enhances the body's ability to prepare for impact, which is crucial for reducing injury risk and improving landing stability (Jones et al., 2016). However, while vertical impact forces showed significant reductions, horizontal ground reaction forces and muscle coactivation between agonist and antagonist muscles did not exhibit significant changes. This may suggest that improvements in horizontal force absorption and intermuscular coordination require longer or more specialized training interventions, as noted by Niespodziński et al. (2021)

Despite these promising results, the conclusions of this study must be interpreted with caution, particularly regarding their generalizability to a broader population of gymnasts. One of the main limitations of this project is the small sample size and the use of a convenience sample. The participants were non-randomly selected from two specific gymnastics clubs, limiting the representativeness of the findings. Given the diversity in artistic gymnastics, including differences in skill levels, training methods, and competition experience, it is challenging to apply these conclusions universally. Moreover, external factors such as prior physical conditioning and equipment variability may have influenced the results but were not fully controlled in this study.

To build on these findings, future research should focus on including a larger and more diverse sample of gymnasts, incorporating variations in gender, age, skill level, and competitive background. Additionally, studies investigating longer or more intensive training interventions could provide deeper insights into whether the observed improvements in impact control and neuromuscular activation can be sustained or further enhanced over time. Further exploration of horizontal

landing forces and muscle coactivation strategies may also contribute to a more comprehensive understanding of injury prevention and performance optimization in gymnastics.

From a practical standpoint, this study highlights the importance of incorporating specific physical preparation programs into gymnastics training. Targeted exercises aimed at improving strength, mobility, and coordination have proven to be effective in enhancing landing control and potentially reducing lower limb injury risks (Nosaka et al., 2001). The observed increase in torque production for dorsiflexion/plantar flexion and knee flexion/extension reinforces the necessity of muscle strengthening for joint stabilization during high-impact landings. These insights provide valuable guidance for coaches and physical trainers, emphasizing the role of structured neuromuscular training in optimizing gymnasts' performance and safety.

In summary, while the limited sample size restricts the generalization of these findings, this study reinforces key aspects relevant to artistic gymnastics training. Most notably, it underscores the effectiveness of specific landing preparation in reducing vertical impact forces, improving neuromuscular control, and enhancing force production capacity in lower limb stabilizing muscles. These results provide a strong scientific basis for implementing targeted training programs aimed at improving performance and minimizing injury risks. Despite its limitations, the study highlights the potential long-term benefits of integrating specialized physical preparation into regular gymnastics training, a practice that could significantly contribute to the safety and efficiency of gymnasts' landings.

5. General Discussion

In our study, we aimed to ensure that both articles within this research were closely interconnected and contributed to the broader understanding of landing mechanics in artistic gymnastics. The systematic review on the impact of landings and ground reaction forces, alongside the experimental study evaluating the effects of a specific physical preparation protocol, provides a comprehensive perspective on performance optimization and injury prevention in gymnasts. The increasing volume of research, with approximately 8,000 studies published since 1920, highlights the significance of understanding landing dynamics and their implications for gymnasts, given the high intensity and complexity of their routines.

A key finding from the systematic review is that competitive gymnasts experience higher ground reaction forces compared to recreational athletes in other jumping sports, such as basketball and volleyball (Seegmiller & McCaw, 2003). This underscores the necessity of training strategies that mitigate the risk of impact-related injuries, particularly for high-performance athletes who perform a substantial number of landings in daily training (Mills et al., 2008).

Furthermore, the review identified that execution errors in landings, such as inter-limb asymmetries and insufficient hip flexion, contribute significantly to injury risk (Mills et al., 2010). The experimental study complements this information by demonstrating that a six-week targeted landing preparation protocol led to a significant reduction in vertical ground reaction forces, along with an increase in time to peak force. These findings suggest improved impact absorption and enhanced neuromuscular control during landings, in agreement with previous studies (Verniba et al., 2017; Zech et al., 2010). These results align with previous research emphasizing the importance of neuromuscular training in reducing landing forces and optimizing impact control in high-performance gymnasts (McNitt-Gray, 1993; Verniba et al., 2017).

The analysis of movement patterns during landings in both the systematic review and the experimental study reveals notable differences between gymnasts of varying skill levels. Mizutori et al. (2021) observed that more experienced gymnasts develop neuromuscular coordination patterns that promote safer and more efficient landings. The results of the experimental study indicate that specific physical training can play a crucial role in refining these skills. The observed increase in muscle activation during the pre-activation phase aligns with existing literature emphasizing the importance of strong muscle pre-activation for efficient impact absorption and injury prevention (Jones et al., 2016).

Another key aspect highlighted in the review is the variation in landing strategies between men and women, as well as differences based on training experience. The literature indicates that these variations influence sagittal range of motion at the knees and hips (Straker et al., 2022). Given the individuality in task responses, our findings reinforce the need for tailored training programs that consider both external factors and each gymnast's experience to optimize performance and minimize injury risk.

6. General Conclusions

In summary, this dissertation aimed to assess the impact of a six-week specific landing physical preparation protocol on high-performance athletes in Women's Artistic Gymnastics and Men's Artistic Gymnastics. The general objective was supported by specific aims, including the analysis of electromyographic activity, ground reaction forces, isokinetic measures and changes in landing biomechanics following the intervention. The study also sought to identify improvements in landing stability, motor control, and overall performance, ultimately providing evidence-based recommendations for coaches and athletes to enhance landing safety and performance in artistic gymnastics.

The exploratory structure of this work, following a mixed, allowed for a comprehensive examination of the existing literature regarding landings in artistic gymnastics. The systematic review article titled "THE IMPACT OF LANDINGS AND GROUND REACTION FORCES IN ARTISTIC GYMNASTICS" highlighted crucial biomechanical aspects, addressing gaps in the current understanding of landing dynamics. The subsequent experimental study, "WHAT IS THE INFLUENCE OF SPECIFIC PHYSICAL PREPARATION TRAINING IN REDUCING THE IMPACT OF LANDINGS IN ARTISTIC GYMNASTICS ELEMENTS?", provided practical insights and data that reinforced the importance of targeted physical preparation.

The hypotheses outlined at the outset anticipated significant improvements in landing performance post-intervention. We expected increased lower limb muscle activation during both pre-activation and landing phases, as measured by EMG. Additionally, we hypothesized that ground reaction forces during landings would show a significant decrease, indicating improved force absorption and transmission capabilities. Furthermore, isokinetic testing was expected to reveal enhanced force production capacity in the muscles involved in floor landings, along with improved overall coordination in controlling movements during landings.

Overall, the findings of this dissertation indicate that implementing a specific physical preparation program can significantly enhance landing performance among gymnasts. By increasing muscle activation and decreasing ground reaction forces, the protocol not only improves performance but also reduces the risk of injury during landings. Coaches and athletes are encouraged to incorporate specific training strategies that focus on strength, mobility, and coordination to optimize landing techniques.

Despite the limitations of the small sample size, this research contributes valuable insights to the field of artistic gymnastics and lays the groundwork for future investigations. Expanding the scope of research to include larger and more diverse samples will be essential to validate and generalize these findings across different populations within the sport. In conclusion, the integration of scientific principles into training practices can lead to safer and more effective performances, ultimately benefiting the long-term health and success of gymnasts.

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Attachments

Appendix 1 - Informed consent



Consentimento informado

Qual a influência do treino de preparação física específica na diminuição do impacto das receções em elementos de ginástica artística?

A estudante do Mestrado em Treino de Alto Rendimento da Faculdade de Desporto da Universidade do Porto, Beatriz Freitas de Oliveira Silva, no âmbito da realização da sua dissertação encontra-se a desenvolver um projeto de pesquisa com intervenção, orientada pela Professora Doutoras Lurdes Ávila Carvalho e pela Professora Doutora Filipa Sousa.

O nosso objetivo geral, neste estudo é comparar a taxa de sucesso de receções e os seus respetivos impactos em elementos no solo na ginástica artística, antes e após aplicação de um protocolo de preparação física específica.

Num primeiro momento, pretendemos avaliar os ginastas na realização de 6 elementos, que garantem a realização de receções que após rotações do corpo num ou mais eixos. Os elementos selecionados foram; mortal à frente, mortal atrás, mortal à frente com meia e uma pirueta, mortal atrás com meia e uma pirueta. As receções dos ginastas serão avaliadas em plataformas de força sobrepostas com colchões similares aos utilizados no treino e com recurso a eletromiografia de superfície.

Em seguida, pretendemos aplicar um mesociclo de preparação física específica, com a duração de 6 semanas direcionado totalmente no aperfeiçoamento das receções de elementos propostos no solo. O protocolo terá a duração aproximada de 10 minutos e irá ser aplicado 3 vezes por semana no início do treino após prévia ativação geral.

No final do período de intervenção os ginastas serão novamente avaliados na realização dos mesmos elementos e serão comparadas as receções realizadas antes e após o programa de treino. Esperamos conseguir observar melhorias significativas na técnica das mesmas entre a 1a e a 2a avaliação, e que estas se traduzam na redução dos impactos no solo experimentados pelos ginastas em análise.

Os dados recolhidos nesta análise serão confidenciais e usados com o intuito de servirem de base para a pesquisa realizada.

Eu, (nome completo) _____ ,
encarregado(a) _____ de _____ educação _____ do(a) _____ ginasta _____ , tomo conhecimento e declaro ter lido e compreendido este documento, bem como as informações verbais que me foram fornecidas pela/s pessoa/s que acima assina/m. É garantida a possibilidade de, em qualquer altura, recusar participar neste estudo sem qualquer tipo de consequências. Desta forma, aceito participar neste estudo e permito a recolha e utilização dos dados que de forma voluntária forneço, confiando em que apenas serão utilizados para esta investigação e nas garantias de confidencialidade e anonimato que me são dadas pelo/a investigador/a.

O(a) encarregado(a) de educação:

(assinatura) _____

Data: ____/____/____

O Investigador responsável

Nome: Beatriz Freitas

Email: beatriz.freitas2300@gmail.com

Assinatura: _____

Appendix 2 - Declaration of the Ethics Committee regarding the Study Protocol



COMISSÃO DE ÉTICA

Declaração

Para os devidos efeitos declara-se que o projeto CEFADÉ 13 2023 *"What is the influence of specific physical preparation training in reducing the impact of landings in artistic gymnastics elements?"* submetido à Comissão de Ética da Faculdade de Desporto da Universidade do Porto por Beatriz Silva foi aprovado por ter em conta os requisitos éticos recomendados.

Porto, 10 de outubro de 2023

A Presidente da Comissão de Ética

A handwritten signature in blue ink, which appears to read 'Isabel Maria Ribeiro Mesquita'.

Isabel Maria Ribeiro Mesquita
(Professora Catedrática)

Appendix 3 – Registration paper for athletes with number of successful landings

[illegible]

IT: Início do treino

FT: Final do treino

Na zona dos "Mortais" colocar numeração (1/4,2/4,3/4,4/4) de acordo com o número de mortais com receções estáticas.

Appendix 4 – Registration paper for athletes with sound control of successful landings

[illegible]

IT: Início do treino

FT: Final do treino

Na zona dos "Mortais" colocar numeração de 1 a 3 de acordo com a explicação abaixo redigida

Escala elaborada com recurso à app “Decibel X” onde o som de cada receção é captado por um telemóvel ou tablet.

1. ZONA VERDE da app – menos de 80 decibéis no momento do embate dos pés no solo, recepção amortecida,

- 2; ZONA AMARELA da app – entre 80 e 90 decibéis no momento do embate dos pés no solo,

- 3 ZONA VERMELHA da app – mais de 90 decibéis no momento do embate dos pés no solo

THE IMPACT OF LANDINGS AND GROUND REACTION FORCES IN ARTISTIC GYMNASTICS: A SYSTEMATIC REVIEW

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Abstract

There is growing concern about the technical execution of gymnastics landings due to the repeated impacts experienced by gymnasts and their potential consequences. Most artistic gymnastics exercises conclude with a landing, during which gymnasts are subjected to very high ground reaction forces. This review aimed to identify and synthesize the available scientific literature on landing techniques across different apparatuses in artistic gymnastics.

Research was conducted between May 11 and 21, 2022, using four databases - Scopus, Web of Science, EBSCO, and PubMed - identified 16 relevant articles after excluding duplicates and articles flagged as ineligible by automation tools. The sport requires more specific research to provide specialists and coaches with comprehensive knowledge about the characteristics of landings on all four apparatuses, and to offer guidance on improving these movements within training contexts. Further investigation into physical preparation and optimal conditions for landing execution is essential. Increasing both the quantity and quality of information could equip coaches with more effective tools for practice, ultimately contributing to the advancement of gymnastics.

Keywords: artistic gymnastics, Landings, Ground reaction forces, Biomechanics

INTRODUCTION

Research in artistic gymnastics has been extensive since the sport's early development. However, interest and research have significantly increased since gymnastics first appeared in the 1928 Olympic Games in Amsterdam, involving both men and women. Since this pivotal moment, the scientific community has shown a growing interest in understanding the biomechanical components of the sport's complex movements as well as the

physiological aspects of its athletes (Prassas, Kwon, & Sands, 2006). Since 2000, there has been exponential growth in scientific research, resulting in a broader and more diverse range of studies in this field.

In gymnastics, all routines conclude with a landing, making proper and safe landings a crucial aspect of the sport (Niespodziński et al., 2021). According to Nagano, Ida, Akai, and Fukubayashi (2009), approximately 69–84% of landings are

performed with a failure rate that can lead to injury. Reports by Niespodziński et al. (2021) indicate that peak vertical ground reaction forces can exceed nine times the body weight and occur in less than 0.05 seconds, particularly in apparatuses such as the floor and vault, highlighting the significant forces involved in these landings.

Landing quality is influenced by both subjective factors (e.g., biomechanical aspects) and objective factors (e.g., the mechanical characteristics of the landing area) (Čuk & Marinšek, 2013), as well as the gymnast's motor control and physical preparation. Physical preparation refers to the gymnast's ability to manage the loads encountered during landings. Inadequate conditioning and physical preparation can hinder successful landings and potentially lead to overuse injuries over time. Motor control encompasses the gymnast's ability to manage their movements, including body-space awareness and flight time (Čuk & Marinšek, 2013).

Since every routine on all four apparatuses in women's artistic gymnastics (WAG) and all six apparatuses in men's artistic gymnastics (MAG) ends with a landing, this component significantly impacts the final score of each exercise. The final score reflects the gymnast's performance, with improvements in landing technique potentially reducing penalties for execution errors, as stipulated by the 2022–2024 Code of Points (FIG, 2022). Thus, better landings may lead to fewer penalties and a higher final score.

While improved landing techniques are generally associated with higher competition scores due to reduced execution errors, more specific studies are needed to quantitatively link better landings to increased scores. Further research is required to provide concrete evidence of this relationship.

Research on artistic gymnastics is published across various sports journals. The aim of this review was to identify and synthesize the scientific literature on landing abilities across different gymnastics apparatuses, based on various evaluation

methods. Organizing this information by themes, areas of analysis, and methodologies is intended to assist coaches in teaching correct and safer landings, enhancing movement techniques, and ultimately improving gymnasts' performance in competitions.

METHODS

A systematic review of the available literature was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The research strategy was based on the approach outlined by Sarmiento, Anguera, Pereira, and Araújo (2018). This review was conducted across four databases: Scopus, Web of Science, EBSCO, and PubMed, with deduplication and screening performed using EndNote X20 (Clarivate Analytics, Philadelphia).

The database search was conducted from May 11 to May 21, 2022, using a filter for scientific articles and targeting sports journals. The search key used was: "Artistic Gymnastics AND Landing AND Ground Reaction Forces."

The inclusion criteria for selecting articles were:

1. Inclusion of relevant data on the technical components of landings in gymnastics.
2. Consideration of various methods for studying ground reaction forces in the sport.
3. Inclusion of athletes with experience in artistic or acrobatic gymnastics, particularly in floor elements (men's artistic gymnastics was included due to its potential relevance and applicability to women's artistic gymnastics).
4. Publication in English or Portuguese.

Articles were excluded if they:

1. Did not focus on elements directly related to artistic gymnastics.
2. Did not involve athletes from artistic gymnastics.
3. Lacked relevant data on landings or ground reaction forces.

Following this analysis, duplicates were removed using EndNote X20. The final step involved organizing and cataloging the articles by subject using the "manage attachments" function, which allowed sorting by file name, author name, year of publication, and title. This information was subsequently compiled into a Word document, with the various themes systematically organized by numbers and topics.

Quantitative studies were evaluated to determine their adherence to the following 16 quality criteria: (1) purpose, (2) relevance of background literature, (3) appropriateness of study design, (4) sample description, (5) sample size justification, (6) informed consent procedure, (7) outcome measures, (8) validity of measures, (9) significance of results, (10) analysis, (11) clinical importance, (12) description of drop-outs, (13) conclusions, (14) practical implications, and (15) limitations.

Each criterion was assessed and categorized as: 1 (meets the criteria), 0 (does not fully meet the criteria), or NA (not applicable). To ensure a fair comparison across studies with different designs, a percentage score was calculated as the final measure of methodological quality. This was done by dividing the sum of scores for all relevant criteria by the total number of applicable criteria for each study design. Articles were then classified into three categories based on their percentage score: (1) low methodological quality (score below 50%), (2) good methodological quality (score between 51% and 75%), and (3) excellent methodological quality (score above 75%).

Data extraction was performed by one researcher and subsequently reviewed by a second researcher. Any disagreements were resolved through consensus between the two reviewers.

RESULTS

The initial search yielded 754 titles from the specified databases, which were then imported into reference management software (EndNote X20). Duplicates (82 references) and articles marked as ineligible by automation tools (16 references) were automatically removed. The remaining 656 articles were screened based on their titles and abstracts, resulting in the manual and automated elimination of an additional 572 articles. The full texts of the remaining 84 articles were then selected for in-depth reading and analysis (see PRISMA Flow Diagram – Fig. 1).

The primary reason for study exclusion ($n = 28$) was a lack of relevance to the sport in question. Additional exclusions were due to the inclusion of data from participants in other sports ($n = 23$) and a lack of relevance to the research topic due to insufficient practical application ($n = 17$). Ultimately, 16 studies met the criteria and were included in this review.

Regarding the quality of the studies, the most notable findings were that the mean score for the 16 selected studies was 93.7%. Two publications achieved a perfect score of 100%; no publication scored below 50%; none scored between 51% and 75%; and 14 publications had an overall quality rating of more than 75%.

Two independent reviewers classified the papers based on various major research topics. They evaluated whether: the study's purpose was clearly stated; relevant background literature was reviewed; the design was appropriate for the research question; the sample was described in detail; the sample size was justified; informed consent was obtained; the outcome measures were reliable and valid; the methodology was described in detail; results were reported with statistical significance; the analysis methods were appropriate; the importance for practice was reported; any dropouts were noted; conclusions were appropriate given the study methods; there were any implications for practice based on the

results; and the study's limitations were acknowledged and described by the authors.

Disagreements were resolved through discussions with the co-authors until a consensus was reached. The goal was not to create mutually exclusive categories, as the

same analysis could cover topics related to different categories. Thus, an article classified in one category could also be classified in another category if its content warranted it.

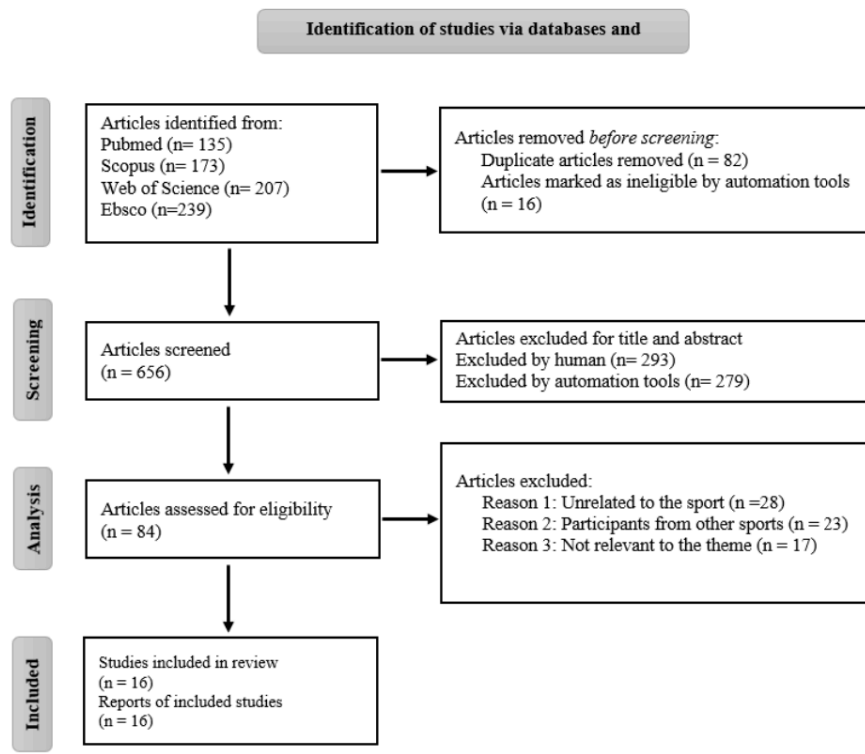


Figure 1. Prisma Flow Diagram of the procedures used for the article search.

Landings in gymnastics and their impact on athlete performance have been the focus of 16 studies. The primary distinction in the analysis of these studies was based on the methodology used, which we categorized as follows: (1) studies using only force plates; (2) studies using detailed

image analysis; (3) studies using electromyography (EMG), force plates, and detailed image analysis; and (4) studies employing various other methods.

Table 1 presents the main topics of the studies included in this review that utilized force plates as the primary research method.

Table 1
Studies using only force plates.

Study	Sample	Procedure	Results and conclusions	Quality score (%)
Glynn, Laird, Herrington, Rushton, and Heneghan (2022)	32 asymptomatic Elite level gymnasts from 3 artistic gymnastic teams. 15 Senior F - 10 Junior F - and 7 Senior M	3 “drop jumps” off the step completing a 180 turn in the air and landing with both feet on the force plate.	No statistical difference between injured and non-injured gymnasts for landing force (p 1/4 0.481) and asymmetry of landing force (p 1/4 0.698). Most participants (69%) demonstrated inter-limb asymmetry of landing forces, observed in injured and uninjured gymnasts. Both magnitude of landing force and inter-limb asymmetries of landing force failed to identify the risk of ankle injury.	93,3
Seegmiller and McCaw (2003)	20 F students between 18 -23 years. 10 members of Division I team with at least 8 years of gymnastics experience. 10 recreational athletes that had a previous involvement in organized group sports.	10 trials of 30, 60 and 90 cm drop jumps on to a force plate.	Gymnasts exposed themselves to higher GRF at 60 and 90 cm than recreational athletes. Gymnasts land with higher impact forces than recreational athletes, raising concerns for repetitive stress injuries because of high-impact loading.	93,3
Seeley and Bressel (2005)	10 high-level F gymnasts competing at level 9, 10 or elite ranked by the USA Gymnastics Federation). 8 collegiate level gymnasts. 2 competitive gymnasts that could successfully perform the Yurchenko vault.	3 trials of Yurchenko vault and round-off on floor with the trail hand contacting a force platform.	Vertical and anterior-posterior GRF, normalized to body weight, were greater (p < 0.05) during the round-off phase of the Yurchenko vault (2.38) than during the floor exercise round-off (2.15). Vertical GRF during both round-off exercises are similar to reaction forces transmitted to upper extremities during other gymnastic skills to lower extremities while running and walking at various speeds.	93,3
Straker, Exell, Farana, Hamill, and Irwin (2022)	7 F, competitive, collegiate, artistic gymnasts (age: 20.5 ± 1.2 years) non injured and actively training at least 3 times per week at a university gymnastics club.	20 drop landings from a 0,72m box onto 2 force plates covered with 2 gymnastics mats.	Group differences (p ≤ .05) reported in the sagittal ROM at the knees and hips, with the men’s strategy eliciting a larger ROM decelerating the body upon impact. Individually favored landing strategy to fulfil the informational constraints and hence supporting the use of a single- subject design. emphasizes the potential injury risk associated with the different informational constraints placed on F landing strategy by the FIG, whilst recognizing the individual gymnasts’ task response.	100

Regarding the studies described in Table 1, only one study included a sample with both sexes (Glynn et al., 2022), while the other three studies focused on female athletes (Seegmiller & McCaw, 2003; Seeley & Bressel, 2005; Straker et al., 2022). Two studies had samples of 10 or fewer athletes (Seeley & Bressel, 2005; Straker et al., 2022), while two studies included more

than 10 athletes (Glynn et al., 2022; Seegmiller & McCaw, 2003). All four studies involved gymnasts, with three specifying that the gymnasts were competing on collegiate teams during the research period (Seegmiller & McCaw, 2003; Seeley & Bressel, 2005; Straker et al., 2022), while the fourth study focused on elite gymnasts (Glynn et al., 2022).

In studies using only force plates to evaluate ground reaction forces (GRF), gymnasts performed various tasks on the force platform. Most studies assessed the final phase of a movement, such as a two-footed landing after a 180° turn from a step (Glynn et al., 2022), drop jumps from heights of 30, 60, and 90 cm (Seegmiller & McCaw, 2003), and drop jumps from a 0.72 m box (Straker et al., 2022). In contrast, Seeley and Bressel (2005) evaluated participants during the initial phase of the Yurchenko vault and round-off on the floor, with the trail hand contacting the force platform.

Three articles reported significant statistical differences in their results (Seegmiller & McCaw, 2003; Seeley & Bressel, 2005; Straker et al., 2022), while one article found no significant differences in landing force or asymmetry of landing

force (Glynn et al., 2022). Glynn et al. (2022) observed inter-limb asymmetry in landing force among both injured and uninjured gymnasts. Seegmiller and McCaw (2003) found that gymnasts experienced higher impact forces compared to recreational athletes. Seeley and Bressel (2005) reported that vertical and anterior-posterior reaction forces, normalized to body weight, were greater during the round-off phase of the Yurchenko vault compared to the floor exercise round-off. Additionally, Straker et al. (2022) found differences in sagittal range of motion (ROM) at the knees and hips between groups, with the men's landing strategy resulting in a larger ROM to decelerate the body.

Table 2 presents the main topics of the studies included in this review that used image analysis as the primary research method.

Table 2
Studies using detailed image analysis

Study	Sample	Procedure	Results and conclusions	Quality score (%)
Čuk and Marinšek (2013)	12 M gymnasts from the Slovenian national gymnastics team (Age: 18.75 ± 2.63 years).	1 stretched forward and backward salto with 1/2, 1/1 and 3/2 turns on a competition floor, with 24 Parotec hydrocell pressure sensors for each foot and three video high quality cameras	Average deduction for landing was 0.30 points, which can be described as an average error. All analyzed predictors defined asymmetries between lower limbs (speeds and angles).	93,3
Mizutori, Kashiwagi, Hakamada, Tachibana, and Funato (2021)	59 M gymnasts (Age: 16.4 ± 2.9 years), including 48 junior elite national gymnasts in national training camp.	2 straight arm press to handstand on a force platform with image capture using a video camera (Basler AG, Type A602fc-2).	Larger shoulder flexion moments observed in less-skilled compared with highly- skilled performers. Larger hip flexion moments were observed in highly- skilled performers at 52% and normalized time of straight arm press to handstand. Major differences between highly skilled and less-skilled performers were observed in hip joint moment production as it shifted from extension to flexion from the leg horizontal position to the handstand position in highly skilled gymnasts.	93,3

Regarding the studies using detailed image analysis, both focused on male gymnasts. Čuk and Marinšek (2013) included a sample of 12 gymnasts with an average age of 18.75 ± 2.63 years, while Mizutori et al. (2021) studied 59 gymnasts with an average age of 16.4 ± 2.9 years. Both samples comprised gymnasts on national teams (Čuk & Marinšek, 2013; Mizutori et al., 2021).

Čuk and Marinšek (2013) evaluated a stretched forward and backward salto with $\frac{1}{2}$, $\frac{1}{1}$, and $\frac{3}{2}$ turns on a competition floor, using three high-quality cameras. Mizutori et al. (2021) assessed a two straight-arm press to handstand, using just one high-quality camera.

Both studies found significant statistical differences in their results (Čuk & Marinšek, 2013; Mizutori et al., 2021) and identified asymmetries between the legs in terms of speeds and angles. Mizutori et al. (2021) observed that major differences between highly skilled and less-skilled performers were in hip joint moment production, specifically the transition from extension to flexion as the leg moved from a horizontal position to a handstand, with highly skilled gymnasts demonstrating more efficient movements.

Table 3 presents the main topics of the studies included in this review that used a combination of three methods: (1) electromyography (EMG), (2) force plates, and (3) detailed image analysis.

Regarding the studies described in Table 3, only one study included a sample with both sexes (Król et al., 2020), while the other four studies involved only male athletes (Chris Mills et al., 2008; Niespodziński et al., 2021; C. Wu et al., 2019; C. L. Wu et al., 2019). Two articles focused on case studies with a single athlete each (Chris Mills et al., 2008; C. L. Wu et al., 2019), one article had a sample of 6 athletes (C. Wu et al., 2019), and two articles had samples of more than 10 athletes: one with 11 athletes (Król et al., 2020) and the

other with 46 athletes (Niespodziński et al., 2021). Of these studies, three included gymnasts who were part of national teams (Król et al., 2020; C. Wu et al., 2019; C. L. Wu et al., 2019), while the other two focused on elite-oriented gymnasts (Chris Mills et al., 2008; Niespodziński et al., 2021), with the latter also including age-matched non-athletes as control groups.

Three studies analyzed floor elements such as somersaults (Król et al., 2020; C. Wu et al., 2019; C. L. Wu et al., 2019), one analyzed vault elements (forward and backward) (Chris Mills et al., 2008), and one analyzed a nonspecific gymnastics movement (countermovement jump) (Niespodziński et al., 2021). All five articles reported significant statistical differences in their results (Król et al., 2020; Chris Mills et al., 2008; Niespodziński et al., 2021; C. Wu et al., 2019; C. L. Wu et al., 2019).

Niespodziński et al. (2021) found that gymnasts achieved 13% higher values ($p = 0.04$) for relative peak ground reaction forces (GRFs) compared to controls. C. Wu et al. (2019) reported that the absolute symmetry index (ASI) of flexion in lower limb joints was less than 10%, indicating excellent landing symmetry in sports performance. Król et al. (2020) found that the countermovement jump (CMJ) exhibited the highest levels of vertical impulse, velocity, and displacement, followed by the tucked backward somersault (TS), piked backward somersault (PS), and backward handspring (HS). C. L. Wu et al. (2019) observed that the lower extremity joints flex actively just before touchdown, continue flexing rapidly during the initial impact phase, and then extend to resist the impact force and maintain body posture during the terminal impact phase of the landing. Chris Mills et al. (2008) found that muscle activation profiles revealed relatively high levels of co-contraction prior to landing.

Table 4 presents the main topics of the studies included in this review that used different methods in their research.

Table 3

Studies using electromyography (EMG), force plates and detailed image analysis

Study	Sample	Procedure	Results and conclusions	Quality score (%)
(Niespodziński et al., 2021)	46 M Elite-oriented gymnasts that had started training at the age of 6–7 years 58 M non-athletes age matched. G1: 8–10-year-olds, G2: 12–14-year-olds and G3: 18–25-year-olds.	3 counter movement jumps on to a force plate with simultaneous surface electromyography (SEMG) recording.	Gymnasts achieved 13% higher values ($p = 0.04$) of relative peak GRFs in comparison with controls. It was especially seen in 8–10-year-olds: G1 presented 33% higher ($p = 0.03$) results than C1 and G2. Gymnasts aged 8–10 years showed the highest relative peak GRFs, as well as its rate of development.	93,3
(C. L. Wu et al., 2019)	17-Year-old international-level M gymnast from the Chinese artistic national team competing in World Cups, with no musculoskeletal injuries for at least 6 months prior.	3 backward somersaults in a force plate with synchronized motion capture system (Qualisys Oqus) and a surface electromyogram system.	Different symmetry in kinematics, kinetics and EMGs between the left and right legs occur during the landing. In the impact phase the difference between flexions of both hip and knee joints was within 5 degrees and the difference in ankle dorsiflexion was within 10 degrees. the absolute symmetry index (ASI) of flexion lower limb joints were less than 10%.	93,3
(Król, Klyszech-Morciniec, & Bacik, 2020)	11 healthy artistic gymnasts (9 F and 2 M) members of the Polish national gymnastics team.	1 TS, 1 PS, 1 HS and a CMJ recorded with 6 infrared cameras, synchronized with a module for wireless EMG activity of 8 muscles, and 1 force plate.	CMJ showed the highest level of vertical impulse, velocity, and displacement followed by the TS, PS, and HS. In the take-off phase of Jumps with rotation the average muscle activation levels of the biceps femoris were significantly higher and of the rectus femoris significantly lower than in the CMJ.	93,3
(C. Wu et al., 2019)	6, 17 years old international-level M gymnast from the Chinese artistic national team competing in World Cups, with no musculoskeletal injuries for at least 6 months prior.	3 BS in a force plate with synchronized motion capture system (Qualisys Oqus) and a surface electromyogram system.	In BS landings gymnast's 1st extend their lower extremity joints to increase the moment of inertia, and reducing the body's angular velocity before touchdown. The lower extremity joints flex actively just before touchdown, continue flexing actively and rapidly in the initial impact phase, and then extend to resist the impact force and maintain body posture during the terminal impact phase of the landing.	93,3
(Chris Mills, Pain, & Yeadon, 2008)	1 M Elite Gymnast with 1,77m and 75 kg.	Gymnast performed 1 forward rotating and backward rotating vault using a force place on the landing area, EMG and three-dimensional motion data using 12 Vicon 624 cameras.	High levels of co-contraction occur prior to landing. As there were already high activation levels the eccentric muscle forces were immediately large, but the concentric forces rapidly fell due to the fact that the muscles were shortening rapidly. This gave a rapid rise in the net extensor torque necessary to control the landing and this effect is likely to have occurred during the landing for the subject.	93,3

Table 4
Studies using other methods

Study	Sample	Procedure	Results and conclusions	Quality score (%)
Sonvico et al. (2019)	30 Elite gymnasts (15 M, 15 F) between the ages of 16 to 30 years members of the British Artistic Gymnastics elite senior and junior training program.	Lumbar spine and LLS ROM during a SLT were measured, using the Dorsa Vi: Vi PerformTM system.	Maximal lumbar spinal movements were 64.23° (6.34°) for flexion and 25.89° (11.14°) for extension. During the SLT, participants performed lumbar spine flexion of 15.96° (8.80°), when considered as a single segment. When considering the lumbar spine as a two-segment model the LLS position during the SLT was towards end.	93,3
Rohleder and Vogt (2019)	25 M gymnasts with 16 years of age competing in World Championships. (WC13),(WC15),(WC17).	All floor exercise routines (n= 25) performed in the men's floor exercise finals at the World Championships in 2013 (WC13), 2015 (WC15) and 2017 (WC17) were examined using video analysis and official judges scores	Current changes in world elite floor exercise gymnasts are characterized by generally decreased score levels due to recent rule changes in the current punctuation code (2017). Focus on stick landings is particularly recommended, however current trends in composing floor exercise routines lead to increased landing errors and, thus lead to decreased final scores.	86,7
Kirialanis, Malliou, Beneka, and Giannakopoulos (2003)	162 gymnasts (83 M and 79 F athletes) participating in the Greek artistic gymnastics' championships.	Gymnasts were observed during 1999-2000 season with personal consultations to register any injury occurring during competitions or training.	A total of 151 injuries were reported for the 12-month experimental period. 93 (61.6%) acute injuries and 58 (38.4%) overuse syndromes. The rate of mild injuries was 26.8% (25 cases), that of moderate injuries was 44% (41 cases), and that of major injuries was 29% (27 cases) (no significant difference between them).	92,9
C. Mills, Pain, and Yeadon (2009)	1 subject-specific 7 link wobbling mass model of a gymnast.	A 7-link wobbling mass model representing the gymnast was constructed in visualNastran 4D (VN4D) to simulate the first 100 ms of landing on a competition gymnastics mat. Experimental exercises were forward (FS) and backward rotating somersault (BS) vaults.	The successful minimization of ground reaction forces (GRF) during landing led to higher internal loading than the matching simulation. Minimizing internal bone bending moments gave low peak GRF with an initial time history that looked more similar to the matching performance.	92,9
C. Mills, Yeadon, and Pain (2010)	A multi-layer model of a gymnastics competition landing mat and a subject-specific 7 link wobbling mass model of a gymnast.	The gymnast-mat model has been evaluated from experimental forward (FS) and backward rotating somersault (BS) vaults.	The optimization of 6 landing mat parameters ($\pm 20\%$ bounds) for the FS and BS vault resulted in the peak GRF being reduced. Gymnast model maintained an acceptable landing technique according to the F.I.G. criteria. The stiffness of the current competition landing mat is optimum and a 20 % change in landing mat damping results in only a small reduction in internal forces within the gymnast. Increased mat damping may be associated with increased forefoot loading.	100

Regarding the articles described in the fourth table, two studies included samples with both men and women (Kirialanis et al., 2003; Sonvico et al., 2019), one study involved only men (Rohleder & Vogt, 2019), and two studies used a wobbling mass model of a gymnast as their subject (C. Mills et al., 2009; C. Mills et al., 2010). Two studies had samples of 30 or fewer athletes (Rohleder & Vogt, 2019; Sonvico et al., 2019)—30 in the first and 25 in the second—while one study had a sample of 162 athletes (Kirialanis et al., 2003). Besides the wobbling mass models used by C. Mills et al. (2009) and C. Mills et al. (2010), the other three studies included gymnasts participating in international championships (Kirialanis et al., 2003; Rohleder & Vogt, 2019) and members of National Elite teams (Sonvico et al., 2019).

Two studies analyzed a wobbling mass model of a gymnast using a computer program called VisualNastran 4D (C. Mills et al., 2009; C. Mills et al., 2010). One study analyzed routines using video analysis and official judges' scores (Rohleder & Vogt, 2019), another used a longitudinal method observing gymnasts during the 1999-2000 season with personal consultations to register any injuries (Kirialanis et al., 2003), and one utilized the Dorsa Vi: Vi Perform™ system to measure lumbar spine and low lumbar spine (LLS) range of motion (ROM) during a simulated landing task (SLT) (Sonvico et al., 2019).

Sonvico et al. (2019) found that during the SLT, participants achieved lumbar spine flexion of 15.96° ($\pm 8.80^\circ$) when considered as a single segment. When considering the lumbar spine as a two-segment model, the LLS position during the SLT was near the end range of anterior pelvic tilt, indicating LLS extension. Rohleder and Vogt (2019) reported that elite floor exercise gymnasts generally experienced lower scores due to recent changes in the 2017 scoring code. Kirialanis et al. (2003) reported that the rate of small injuries was 26.8% (25 cases), moderate injuries were 44% (41 cases), and major injuries were 29% (27 cases). C. Mills

et al. (2009) found that successful minimization of ground reaction forces (GRF) during landing led to higher internal loading compared to the simulation. C. Mills et al. (2010) demonstrated that optimizing six landing mat parameters ($\pm 20\%$ bounds) for forward and backward rotating vaults resulted in reduced peak ground reaction forces.

DISCUSSION

The aim of this review was to identify and synthesize the existing scientific literature on landing abilities across different apparatuses in artistic gymnastics, based on various evaluation methods. Additionally, this review seeks to provide artistic gymnastics coaches with relevant information to enhance landing techniques and, in turn, improve their gymnasts' performance. After a thorough analysis, it was determined that the most effective way to present the results is by categorizing the research topics based on the methodology used: (1) force plates only, (2) detailed image analysis, (3) a combination of electromyography, force plates, and detailed image analysis, and (4) other methods.

Force platform assessments have been widely used to examine impact forces and assess injury risks in various gymnastics tasks (Glynn et al., 2022; Seegmiller & McCaw, 2003; Seeley & Bressel, 2005; Straker et al., 2022). Recent research by Leite et al. (2023) highlights that the force platform is also the most commonly used instrument in acrobatic gymnastics, paralleling its role in artistic gymnastics.

Data from the reviewed studies show that both sexes were included in the samples, demonstrating the similarities and transferability of landing techniques between women's artistic gymnastics (WAG) and men's artistic gymnastics (MAG) across several exercises. However, Straker et al. (2022) found that men and women employ different landing strategies, resulting in variations in the sagittal range of

motion (ROM) at the knees and hips. Specifically, men use a larger ROM to decelerate the body upon landing.

In WAG's code of points, any leg separation, regardless of size, is considered an error after landing an acrobatic element and results in a 0.1 point deduction from the final execution score (FIG, 2022). These differences in landing techniques between WAG and MAG may influence the incidence of traumatic knee and ankle injuries, particularly among female gymnasts (Kerr, Hayden, Barr, Klossner, & Dompier, 2015).

These findings suggest that landing strategies are individually adapted to meet specific informational constraints, supporting the use of single-subject designs (Straker et al., 2022). This also underscores the potential injury risks associated with the FIG code of points, particularly its constraints on female gymnasts' landing strategies, while acknowledging the individual responses of gymnasts. A closer analysis of the FIG code of points and its penalties could help reduce risky movements. For instance, allowing greater leg separation during landings could mitigate the impact and instability, potentially leading to less painful and more stable landings. This is an aspect that coaches could address in training (Straker et al., 2022).

The studies analyzed focused on athletes aged 14 and older, specifically Junior and Senior competitors, ensuring that the participants had substantial experience, often reported as more than 20 hours of practice per week (Seeley & Bressel, 2005). This experience is essential for proficiency in the evaluated elements.

Three articles provided detailed information on sample characteristics, including sex, age, years of experience, competitive level, and practice hours (Seegmiller & McCaw, 2003; Seeley & Bressel, 2005; Straker et al., 2022). Such data is valuable for understanding athletes' performance in the exercises studied. However, Glynn et al. (2022) only included

information on sex, age, and anthropometrics, which limits the interpretation of their results and their practical implications due to the lack of data on athlete experience and practice volume.

Drop jumps were the most commonly analyzed exercise on force platforms, primarily due to their controlled experimental setup. This exercise effectively replicates the rapid impact forces gymnasts experience during landings (Fransz, Huurnink, Kingma, Verhagen, & van Dieën, 2013). However, only one study specifically evaluated gymnastics movements (Seeley & Bressel, 2005), focusing on the Yurchenko vault and round-off on the floor, with the trail hand making contact with the force plate. This in-depth analysis provided valuable insights into improving technique and movement quality.

When comparing similar moments from different apparatuses, such as the round-off phase of the Yurchenko vault and the floor exercise round-off, Seeley and Bressel (2005) found that vertical and anterior-posterior reaction forces were higher in the Yurchenko vault. Despite this, both skills exhibited substantial reaction forces. The differences were likely due to the varying approach distances: 20 meters for the Yurchenko vault and approximately 7 meters for the floor round-off. The shorter approach distances in floor exercises result in lower velocities during the round-off (Seeley & Bressel, 2005). Additionally, gymnasts are constrained to the floor routine area, whereas the Yurchenko vault allows for greater distance and height.

These findings highlight the need for further research focused on methods to reduce reaction forces, particularly in the upper limbs during floor exercises and other gymnastics skills that involve high loads.

Seegmiller and McCaw (2003) found that gymnasts experience higher ground reaction forces (GRFs) compared to recreational athletes from other jumping sports, such as basketball and volleyball. This difference is likely attributed to the repetitive high loads encountered during

gymnastic landings, which can impact performance and increase injury risk. While repeated exposure to these forces should contribute to improvement, the study suggests the opposite, potentially due to insufficient strength training, lack of cushioning, inadequate coaching, or training on varied surfaces. Musculoskeletal stiffness plays a role in regulating the storage and reuse of elastic energy, and gymnasts adjust their total body stiffness according to landing conditions (Leite et al., 2023).

Glynn et al. (2022) observed inter-limb asymmetry in both injured and non-injured gymnasts, without significant differences in landing force asymmetry. This suggests that general lower limb asymmetry is common among gymnasts and may not directly correlate with ankle injuries. Further research is needed to explore additional measures for assessing landing performance and injury risk, taking into account a broader range of tasks.

The high impact forces experienced by gymnasts raise concerns about repetitive stress injuries. Proper landing technique instruction has been shown to reduce impact loads in child and adolescent recreational athletes and gymnasts (McNair & Prapavessis, 1999). Training gymnasts in effective landing techniques may help minimize injury risks associated with repetitive high-impact forces on the lower extremities.

Detailed image analysis provides valuable tools for examining gymnastics elements with high precision and identifying common errors. Čuk and Marinšek (2013) used kinematic data to accurately measure the temporal and dynamic characteristics of landings.

The two reviewed studies included Junior and Senior athletes from Men's Artistic Gymnastics (MAG) national teams in Slovenia (Čuk & Marinšek, 2013) and Japan (Mizutori et al., 2021). The high level of experience among these gymnasts was evident, as Mizutori et al. (2021) noted a mandatory minimum of 10 years of competitive experience, ensuring

proficiency in performing gymnastics skills. However, Mizutori et al. (2021) also included less-skilled gymnasts with fewer years of practice to compare kinematic and joint movement profiles across different skill levels.

Mizutori et al. (2021) found that less-skilled performers exhibited larger shoulder flexion moments compared to highly-skilled gymnasts. In contrast, larger hip flexion moments were observed during the straight arm press to handstand (SAPH). Given that SAPH demands more balance than muscle strength (Mizutori et al., 2021), more experienced athletes are able to perform this element more efficiently by positioning their center of mass correctly, thereby minimizing excessive muscle use.

Kochanowicz et al. (2019) emphasized the importance of analyzing joint moments and moment profiles at different performance levels to assess a gymnast's ability to coordinate movement patterns, such as neural control and skill level.

Evaluating a gymnast's ability to coordinate joint moment patterns is crucial for developing a "highly-skilled" performer (Mizutori et al., 2021). As such, coaches play a key role in implementing training methods to improve gymnasts' coordination of these patterns during their movements.

Both studies focused on specific gymnastics movements, providing valuable insights for practice—both when performed correctly and with errors. Čuk and Marinšek (2013) primarily examined how symmetry or asymmetry in acrobatic movements impacts landing quality.

Čuk and Marinšek (2013) found that landing errors led to an average deduction of 0.30 points, considered a moderate mistake according to the FIG code of points (FIG, 2022). Their analysis revealed asymmetries between the gymnast's lower limbs, influenced by varying speeds and angles.

From a motor control perspective, Čuk and Marinšek (2013) suggested that correct landings are typically achieved in competitions. Controlling the landing is easier after a well-executed salto, which

requires optimal angular momentum, longer flight duration, and increased angular velocity around both the transverse and longitudinal axes. To avoid asymmetric landings, gymnasts must generate sufficient height, greater angular momentum, and improve angular velocity.

These findings indicate that addressing asymmetry should be a key focus in practical training. Coaches are instrumental in ensuring young gymnasts learn to land as symmetrically as possible, which is essential for improving performance and reducing errors (Čuk & Marinšek, 2013).

The combination of electromyography (EMG), force plates, and detailed image analysis offers a more comprehensive understanding of gymnastics movements. These methods enable a detailed assessment of muscular activation, impact forces, and the biomechanics involved in landing strategies.

Among the five studies presented in Table 3, only two employed case studies (Chris Mills et al., 2008; C. Wu et al., 2019; C. L. Wu et al., 2019), focusing on individual athletes with unique characteristics. Due to the nature of these case studies, the findings cannot be generalized to other athletes. To ensure proficiency in the analyzed exercises, several studies included only elite-level gymnasts (Król et al., 2020; Chris Mills et al., 2008; C. Wu et al., 2019; C. L. Wu et al., 2019). Additionally, two studies considered the athletes' injury histories over the previous six months (C. Wu et al., 2019; C. L. Wu et al., 2019), emphasizing the importance of musculoskeletal health in performance.

A key finding from Niespodziński et al. (2021) revealed that gymnasts achieved 13% higher relative peak ground reaction forces (GRFs) compared to non-athletes of the same age. Through long-term training, gymnasts develop distinct neuromuscular coordination patterns that enable them to execute safer landings in alignment with the code of points. For instance, Horita, Komi, Nicol, and Kyröläinen (2002) highlighted

that muscle activation and contraction just before touchdown are critical for safe landings. Younger gymnasts, aged 8 to 10, exhibited the highest relative GRFs, likely due to their lack of experience and body control. Given that gymnasts often perform over 200 dismounts per week during training (M. Gittoes, Jr. & G. Irwin, 2012), the frequent repetition of landings increases the risk of musculoskeletal overload and injury, especially in younger athletes (Campbell, Bradshaw, Ball, Pease, & Spratford, 2019).

To reduce injury risk, training routines must be tailored to the athletes' developmental stages. Coaches should monitor not only technique and landing strategies but also track the specific loads experienced during landings.

Four of the reviewed studies focused on specific gymnastics movements, such as backward somersaults and vaults (Król et al., 2020; Chris Mills et al., 2008; C. Wu et al., 2019; C. L. Wu et al., 2019), while Niespodziński et al. (2021) examined the more general countermovement jump (CMJ).

The study by C. L. Wu et al. (2019) found that gymnasts exhibited inter-limb symmetry in kinematics, kinetics, and EMGs during landing. Differences in joint flexion between the hip, knee, and ankle were minimal, resulting in excellent landing symmetry. This symmetry likely arises from the equal distribution of load among the lower limbs (Sabick, Goetz, Pfeiffer, DeBeliso, & Shea, 2006), with internal joint loads influencing landing efficiency. Achieving symmetrical landings requires controlling lower limb kinetics and EMG variables such as ground reaction force (GRF), torque, stiffness, power, and muscle coordination.

Another study by C. Wu et al. (2019) quantified lower extremity muscle activation during backward somersault (BS) landings. Gymnasts initially extend their lower extremity joints to reduce angular velocity before landing, then flex these joints just before touchdown to absorb the impact and maintain posture.

While many studies (M. J. R. Gittoes & G. Irwin, 2012; Glynn et al., 2022; C. L. Wu et al., 2019) have focused on post-ground contact actions during landing, there is a lack of research on joint preparation and torque in the pre-landing phase (Verniba, Vescovi, Hood, & Gage, 2017).

Chris Mills et al. (2008) also examined muscle activation prior to landing, revealing high levels of muscle co-contraction. These activation levels generated large eccentric muscle forces, quickly producing the net extensor torque necessary to control the landing.

The strategies reported by C. Wu et al. (2019) and Chris Mills et al. (2008)—continuous joint flexion and increased muscle activation—should be taught by coaches to enhance gymnasts' ability to absorb impact and prevent injuries. Król et al. (2020) compared different movements and concluded that the countermovement jump (CMJ) produced the highest vertical impulse, followed by tucked and piked backward somersaults and backward handsprings. To maximize performance in acrobatic jumps, it is crucial that the force vector aligns vertically and near the center of mass (COM). Therefore, coaches should focus on shoulder positioning during takeoff, ensuring that gymnasts avoid leaning backward, as this could destabilize them during backward acrobatic jumps (Król et al., 2020).

Different methods are being employed to study ground reaction forces (GRF) and the biomechanics of gymnastics elements that do not fit into the previous categories (Kirialanis et al., 2003; C. Mills et al., 2009; C. Mills et al., 2010; Rohleder & Vogt, 2019; Sonvico et al., 2019). The data from these studies show that not only were gymnasts evaluated, but also models simulating wobbling mass. In the studies by C. Mills et al. (2009) and C. Mills et al. (2010), these models were preferred over human subjects because they accurately calculate bending moments, providing a simple method to determine the magnitude of skeletal loading, which can be linked to

bone fracture risks based on in-vitro tests. This analysis also allows the authors to determine proper landing strategies without exposing gymnasts to GRF and internal forces.

The remaining three studies feature large samples of elite gymnasts competing in international championships, ensuring a higher level of experience and proficiency in the evaluated elements. Rohleder and Vogt (2019) examined the floor exercise finals at the World Championships in 2013, 2015, and 2017, utilizing video analysis and official judges' scores. Their findings suggest that recent rule changes, according to the 2017-2020 code of points, which mandate stuck landings for full scoring credit, have generally led to lower scores for elite gymnasts in floor exercises.

These studies establish a baseline for asymptomatic lumbar spine movements in elite gymnasts, providing valuable insights into upper and lower lumbar spine movements during simulated landings. While stick landings are highly recommended in floor routines, the increasing difficulty of floor exercises has led to more frequent errors, hindering gymnasts from achieving higher scores. As a result, coaches should prioritize enhanced landing technique training during practice sessions.

During the 1999-2000 season, Kirialanis et al. (2003) observed 151 injuries among gymnasts over a 12-month period. Of these, 93 (61.6%) were acute injuries, and 58 (38.4%) were overuse syndromes. The breakdown of injury severity included 25 mild injuries (26.8%), 41 moderate injuries (44%), and 27 major injuries (29%), with no significant differences between categories. The authors concluded that acute injuries occurred more frequently during floor exercises for both sexes, likely due to the extensive time spent on these routines (Caine, Cochrane, Caine, & Zemper, 1989). The large forces exerted on the lower limbs, particularly the ankles and knees during landings, contribute to this high incidence of injuries. These findings highlight the need

for coaches and sports medicine professionals to implement injury prevention programs targeting gymnasts.

When comparing actual data to simulations, C. Mills et al. (2009) demonstrated that successfully minimizing GRF during landings resulted in higher internal forces than the simulations predicted. Reducing internal bone bending moments led to lower peak GRF and a more consistent performance with reduced internal loading. However, altering a gymnast's landing to reduce GRF and mitigate injury risk could, in fact, increase internal loading.

One year later, C. Mills et al. (2010) showed that optimizing six landing mat parameters for forward and backward vaults resulted in reduced peak GRF, while the gymnast models maintained acceptable landing techniques according to the FIG criteria. Although the stiffness of current competition landing mats is deemed optimal, a 20% increase in mat damping only slightly reduced internal forces. However, a more significant increase in damping could potentially reduce injury risks associated with vault landings, though it may also lead to increased forefoot loading.

LIMITATIONS

One limitation of this systematic review is that it only includes studies from four databases, potentially missing relevant publications from other platforms. Another limitation is the inclusion of multiple papers from the same authors, which could lead to inconsistencies in conclusions and result in redundancy on certain topics. Additionally, involving more experts in the quality control process would help enhance the accuracy of the studies analyzed. During the review, it became evident that most of the research is still skill-oriented, with few general approaches to performance training.

CONCLUSION

Research in artistic gymnastics dates back to the mid-1820s, but interest and the volume of studies significantly increased after 1920, with approximately 8,000 studies published since then. A key area of focus has been ground impacts and the associated reaction forces, particularly in elite athletes who undergo high weekly training volumes. The repeated landings from gymnastics elements, which place significant stress on the joints, are believed to contribute to limb overload and performance decline.

The studies reviewed in this research highlight the most commonly used methodologies in this field: (1) studies using only force plates, (2) studies employing detailed image analysis, (3) studies combining EMG, force plates, and detailed image analysis, and (4) studies that utilize multiple methods. The most frequently addressed topics include (1) injury risk, (2) movement patterns, (3) landing strategies, (4) common execution errors, and (5) material properties.

Injury risk associated with gymnastics landings is well-documented across various studies. This review found that gymnasts experience higher ground reaction forces compared to recreational athletes in other jumping sports, such as basketball and volleyball, when performing similar tasks (Seegmiller & McCaw, 2003). This raises concerns about the potential for repetitive stress injuries due to the high-impact loads gymnasts endure. The research highlights two primary types of injuries: acute injuries, which are more common and occur during landings due to trauma (such as sprains, dislocations, or fractures), and chronic injuries, which, although less frequent, still account for 38.4% of cases. According to Kirialanis et al. (2003), "overuse" injuries primarily result from the repeated high loads during landings. While adjustments to training are recommended to reduce injury rates, the current review does not present direct results from intervention studies designed to validate these recommendations.

Further research, particularly intervention studies, is needed to support these findings.

The literature also emphasizes different movement patterns in gymnastics landings, noting that elements on different apparatuses may share similar moment patterns. For instance, the round-off phase of the Yurchenko vault and the floor exercise round-off display comparable movement patterns (Seegmiller & McCaw, 2003). A key difference, however, was observed in the hip joint moments between highly skilled and less-skilled gymnasts (Mizutori et al., 2021). Over years of practice and training, gymnasts develop distinct neuromuscular coordination patterns that enable them to execute safe, technically precise landings in accordance with gymnastics rules.

Significant differences exist in landing strategies between men and women, as well as between athletes of varying experience and training levels. It is widely accepted that men and women use different landing strategies, which result in variations in the sagittal range of motion at the knees and hips. Men typically exhibit a larger range of motion to decelerate their bodies upon impact (Straker et al., 2022). The literature also indicates that gymnasts adopt individualized landing strategies to meet the specific constraints of each task, highlighting the value of single-subject designs in research. Thus, despite external influences, gymnasts demonstrate unique responses to landing tasks.

Landings in gymnastics are often performed with errors, ranging from minimal to significant, which can lead to injury. Common landing errors include inter-limb asymmetries, insufficient element height, inadequate hip flexion, and poor muscle pre-activation prior to ground contact. While improvements in physical conditioning and motor control are generally linked to better landing outcomes, the effectiveness of specific training methods may vary based on the gymnast's age and skill level. Further research is needed to determine which types of preparation are most effective for different groups.

Additionally, more research is required to identify the successful elements of landings that contribute to talent development in gymnastics. It is also essential for future coaching strategies to be grounded in a solid theoretical framework. Strength training, physical conditioning, and specific landing technique training must be rigorously integrated into practice. Collaboration between gymnastics clubs and research laboratories is crucial for promoting regular assessments and safeguarding the well-being of gymnasts.

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