SHOULDER MECHANICS AND INJURY RISK IN AERIAL ACROBATICS: FROM LOAD PATTERNS TO RECOVERY PATHWAYS

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Summary

The shoulder joint is the most mobile, but also the most vulnerable link in the biomechanical chain of the upper extremity, which is especially evident in conditions of increased load when performing aerial acrobatics elements. The article presents a holistic anatomical and biomechanical review of the structures of the shoulder complex and characterizes the main mechanisms of injury that occur during dynamic and static elements with support on the upper extremities. The typical range of peak loads for different grip variants (true, cup, twisted) and their relationship with the shoulder position are analyzed. Particular attention is paid to preventive strategies, in particular, eccentric strengthening of the shoulder rotators, stabilization of the scapula, and training load management. The second part offers a step-by-step four-phase model of rehabilitation after functional overload, with clear criteria for transitioning between phases. The final section outlines the prospects for research on anatomical, hormonal, and gender moderators of injury, with an emphasis on the need for standardization of methodology for meta-analytic reviews.

Objective. To form an integrated resource covering the anatomy of a shoulder, functional biomechanics during training by aerial acrobatics, to develop coaching tips, and to study the epidemiology of injuries.

Research methods. Narrative synthesis (PubMed, Scopus, Web of Science 2015 2025) in combination with the expert experience of the Chief International Judge of the IPSF.

Key words: aerial acrobatics; shoulder joint; traumatism; biomechanics; prevention; rehabilitation; stabilization of the scapula; eccentric strengthening; sports medicine.

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1. Introduction

The popularity of aerial disciplines has led to an increase in the incidence of shoulder injuries: 2.8-5.1 cases per 1,000 hours of training *(Hansen, 2023)*. Effective prevention requires a thorough understanding of the anatomy, biomechanics, and technical requirements of the sport.

Aerialists are eager to showcase their latest stunts and elements on social media, which may look dangerous to an uninformed viewer. At the same time, there are almost no scientific publications that assess the frequency of injuries and accidents in recreational aerial acrobatics groups. As a result, the professional community and the media are spreading guesses and assumptions about the level of risk compared to other sports and fitness activities, but there is a lack of data for a meaningful comparison.

In general, few studies have been published in the circus arts, and those involving aerialists have mostly focused on professional performers or students in specialized training programs. A milestone was a 2009 article that analyzed five years of medical data from Cirque du

Soleil and found a rate of 9.7 injuries per 1,000 performances. The authors concluded that the overall injury rate among performers was comparable to and often lower than some other sports, including women's gymnastics. A similar ten-year study with a focus on injury prediction found 5.1 injuries/1,000 performances, with 89.4% of performers having at least one injury during the follow-up period. Both studies were based on medical records from their organizations.

This approach was later used in other studies: data from students of German circus schools, records of physiotherapists from Australian and Canadian schools, etc. Several authors have used a wider range of methods, such as qualitative interviews or prospective monitoring, which has expanded the understanding of injuries, but there is still a lack of materials about recreational aerialists.

In the context of fitness, a few studies from the 1990s already surveyed participants in various activities about injuries. Despite methodological challenges, these studies showed that direct questionnaires can provide valuable information about the risks for amateurs. A similar approach was taken by the authors of a recent survey on injuries in sport and recreational aerial sports.

The dynamic and diverse circus environment poses additional challenges to collect reliable injury data. Mixed and qualitative methods offer greater opportunities, as the way data are collected determines which injuries are recorded. Traditionally, cases that required medical attention or resulted in loss of training/work time are recorded, but the full picture is much more complex.

The issue of standardization is described in the 2020 IOC Consensus Statement and its 2022 Circus Extension, which proposes common injury categories, severity criteria, and recommendations for clinicians and participants. Although the circus extension was published after the data collection for our study was completed, it shows promise for generating more comparable future work.

A definite breakthrough in this niche occurred in 2023: McBlaine and Davies published the first study dedicated specifically to adult recreational aerial acrobatics students. The authors recorded 184 traumatic events among 367 participants over a year and characterized the types of injuries and risk factors in detail. Despite the significant contribution, these data remain isolated and need to be confirmed in larger samples.

Thus, an objective risk assessment for recreational aerialists is still difficult. Our study aims to determine the frequency of injuries among adult recreational performers, characterize their types, and identify trends that will help develop effective safety measures. The results will also allow us to compare the risks at the recreational level with professional programs and other sports, providing a more balanced assessment of the dangers.

2. Main part

Before delving into the anatomical details, it is worth emphasizing that it is the shoulder girdle that is at the epicenter of injury statistics in aerial acrobatics. In seven prospective studies published in 2019-2025, shoulder injuries accounted for 24% *(Hansen et al., 2023)* to 55% *(Chan et al., 2019)* of all reported injuries, while the average proportion for rhythmic gymnastics is around 18% and for swimming ≈22%. This wide range reflects not only the real variability of the loads, but also methodological differences: different authors operate with incompatible definitions of "injury" (medical care vs. time loss vs. self-report), small samples (< 600), and the dominance of the female community, which potentially distorts the risk assessment for male beginners.

If we compare aerial disciplines with "classic" overhead sports (volleyball, baseball), the key difference is the traction component: the athlete hangs on the joint, while in volleyball/ baseball, a high-speed "throwing" pattern dominates. A similar type of load can be observed in installers or rock climbers, where the proportion of shoulder injuries fluctuates at a similar level (≈ 30–45%). Thus, for correct comparisons, it is necessary to take into account not only the fact of working "overhead" but also the presence of axial overhang.

Critically, most existing studies are case reports or online surveys with a high risk of recall bias: injured people are more likely to answer a questionnaire than those who train painlessly. In addition, statistics rarely distinguish between an "acute episode of pain" and a "clinically confirmed injury," which distorts the severity scales. This lacunar background emphasizes the need for systematic biomechanical validation, which we will discuss further in the following, moving on to the structure and kinematics of the shoulder girdle.

The shoulder complex operates as a single kinematic unit in which the glenohumeral (GH) and scapulothoracic (ST) segments interact synchronously. Flexion and extension, abduction and adduction, as well as internal and external rotation occur in the HG joint; at the same time, the scapula slides over the thorax, performing elevation, lowering, abduction and retraction, upper and lower rotation with a slight anterior or posterior tilt. The total "scapulohumeral" rhythm in a healthy shoulder is about 2:1 – for every two degrees of humerus movement, the scapula adjusts by one degree, relieving the subacromial space.

Anatomically, the shoulder is formed by four joints: HH, acromioclavicular, sternoclavicular, and functional LT. The labrum deepens the socket, and the capsular ligamentous apparatus, together with the negative pressure of the cavity, forms passive stability. Active retention is provided by the rotator cuff – the supraspinatus, subscapularis, psoas, and subscapularis muscles – which compress the head against the socket and, in cooperation with the serratus anterior and trapezius, contribute to the correct rotation of the scapula.

Aerial acrobatics, especially in aerial and dynamic elements, creates an excessive load on the structures of the upper extremity, particularly the shoulder girdle. After analyzing external mechanical factors, such as peak loads in different grips, it is advisable to turn to the internal biomechanical links that ensure stability and mobility in this area.

The shoulder girdle consists of several interdependent joints, both anatomical and functional. Their coordinated work is critical for maintaining the integrity of the kinematic chain "torso – scapula – the humerus – forearm – hand", especially in the conditions of extreme dynamics of acrobatic movements.

Below are the key joints of the shoulder girdle in terms of anatomy, functional load, and role in compensating for stressful influences typical of acrobatic disciplines:

– Glenohumeral (GH) – ball and socket joint, 3° of freedom.

– Acromioclavicular (AC) – flat; axial rotation up to 15°.

– Sternoclavicular (SC) – saddle-shaped; a single bone connection with the axial skeleton.

– Scapulothoracic (ST) is a functional "joint" that is critical for raising the arm above the head.

The posterior chain (inferior/middle trapezius, rhomboids, latissimus dorsi) controls retraction and posterior tilt, while the anterior chain (pectoralis major/minor, upper trapezius) is responsible for the projection and start of clavicle elevation. An imbalance between these groups is often a prerequisite for impingement syndrome.

Aerial disciplines are characterized by combined axial loads with body weight, prolonged traction in the overhead position, and high eccentric demands on the external rotators.

To withstand a disruption or prolonged overhang, the shoulders must remain "active": the scapula in depression and stabilization of the serratus anterior, and the humerus in controlled external rotation. This reduces compression in the subacromial space and prevents microinstability. If the external rotation is weak, the athlete "hangs" on the capsule, which increases the risk of pain and injury.

One of the basic types of grips in aerial acrobatics is the twisted or inverted grip, which is a variant of the upper limb support in which the humerus is in a combination of full internal rotation, horizontal adduction, and slight flexion, and the scapula is simultaneously in the phase of projection and upper rotation. The combination of these movements creates the most favorable mechanical moment for holding the body on the pylon, mast, and canvases, but at the same time significantly reduces the subacromial space.

According to the MRI kinematic studies by Moor et al. (2014) and Meyer et al. (2021), the combination of internal rotation and horizontal adduction does indeed reduce subacromial space by about 15-20%. However, both studies included no more than 20 shoulders and analyzed static postures, ignoring the inertial peaks inherent in dynamic descents in the pylon, mast, or canopy. The methodological difference in the segmentation of MR frames (automatic vs. manual) also affects the absolute values.

The threshold value for the external rotator force of 0.7 N-m kg^{-1} is taken from the tennis *(Kibler et al.)* and volleyball *(Cools et al.)* cohorts and has not yet been validated for vertical traction scenarios. Without direct measurements of aerialists, this figure is still a practical guideline rather than an evidentiary standard.

Regarding "microinstability" (+2 mm of Jobe drift): Hansen et al. (2023) have shown that cranial displacement sometimes decreases after a short specific warm-up, suggesting an elastic rather than a structural cause of the phenomenon. Thus, +2 mm does not always mean pathology.

Summarizing the above biomechanical observations, it is advisable to outline the unresolved issues and methodological limitations that may reduce the generalizability of the results, namely.

– None of the studies stratify the results by acromion morphotype (type I-III), although this can significantly alter the subacromial gap.

– Sex hormonal factors are not considered: estrogen affects collagen and probably capsular stability.

– There are no longitudinal data: whether tendon tissue adapts over time (similar to rock climbers) remains an open question.

If we draw a parallel between other sports, for example, in baseball, the "late cocking phase" is characterized by maximum external rotation but leads to a similar impingement mechanism. This suggests that the critical factor is not the direction of rotation, but the imbalance between the strength of the active stabilizers and the load.

The data strongly supports the need to develop eccentric ER force, but the exact thresholds for pilots have yet to be established. Until large-scale RCTs are available, we use 0.7 N-m kg^{-1} as a "yellow risk zone" rather than a hard cutoff.

In the twisted grip, the GH: ST ratio is temporarily shifted to ≈ 1.5:1 to compensate for the limited external rotation of the shoulder. An upper scapular rotation lag $< 50°$ or ER deficit $> 15°$ is associated with a threefold increase in anterior shoulder pain.

All clinical safety criteria must be met before the twisted grip can be used:

– ER/IR isometric ratio ≥ 0.66;

– 30 seconds of active hanging without pain and "sagging";

– upper scapular rotation ≥ 55° during the lift.

After a detailed analysis of the twisted grip, it is advisable to consider the biomechanical characteristics of other common grip variants – true and cup – for a comprehensive risk assessment. During a typical microcycle, an athlete sequentially moves between these positions; therefore, the cumulative load on the shoulder complex is determined by their sum, not by individual isolated elements.

Each grip modifies the shoulder moment of force, the spatial orientation of the scapular plane, and the proportion of axial traction attributable to passive tissues (capsule, ligaments) compared to active stabilizers. In particular, true grip is characterized by the most neutral kinematics and relatively low peak load; cup grip increases the bending moment in the radiocarpal segment; instead, twisted grip combines internal rotation of the shoulder with horizontal adduction, which potentially reduces the subacromial space and increases the compression component.

Generalized peak load values were obtained by platform dynamics in the static axis (3 s) and, if necessary, extrapolated to dynamic conditions using an inverse dynamics model *(Nicholas & Alderson, 2024)*.

Comparative analysis of different grip variants is key to optimizing a training program, as all three positions – true, cup, and twisted – modify the external load vector, the moment of force in the shoulder joint, and the degree of active stabilizer involvement in different ways. Within one microcycle, athletes systematically alternate between these grips; thus, the cumulative impact can only be assessed by analyzing the full range of technical options.

Assessment of the load transmitted through the upper extremities in aerial acrobatics is a key aspect in the analysis of shoulder injury risks. Most commonly, the applied forces are studied using a forearm platform or strain gauge suspension systems normalized to body weight (BW), which allows for comparison of results between performers of different anthropometries.

The following data were obtained during a 3-second static lunge with the vertical reaction of the support normalized to body weight. At the same time, some methodological limitations should be considered: first, dynamic load peaks, especially during drops or sharp descents, can significantly exceed laboratory values; second, samples in such studies are usually limited (n ≤ 30) and often have gender disparities, which affects the generalization of data. Nevertheless, the relative differences between grip variants remain informative for clinical analysis and overload prevention (Table 1).

Table 1

Peak Shoulder Joint Load During Static Hang in Different Grip Positions (Normalized to BW)

Grip	Shoulder position	Typical tasks	Peak load (× BW)
True	Neutral / light ER	Lifts, revs	0,9–1,2
Cup	Neutral; forearm supination	Static holds, basic inversions	1,0–1,4
Twisted	Full IR + horizontal adductio	Entrances to handspring, dropships	1,5–2,2

The risk classification is based on systematic reviews *(Nicholas & Alderson, 2024; Hansen et al., 2023)* and a Delphi survey (n = 18) of IPSF coaches.

1. Laboratory limitations. The static protocol does not capture inertial loads during descents; the values obtained should be considered as minimal.

2. Cup grip. Increased wrist flexion angle potentially increases the risk of carpal tunnel syndrome despite relatively neutral shoulder kinematics.

3.T wisted grip. The combination of internal rotation and horizontal adduction reduces the subacromial lumen; implementation is advisable only after achieving an ER/IR ratio of ≥ 0.66 and serratus anterior endurance (> 45 s of active hanging).

4. Gender imbalance in the sample. The majority of participants (≈80%) were female; results should be extrapolated to men with reservations due to differences in strength profiles.

Aerial acrobatics places extremely high demands on the functional integrity of the shoulder complex, as this anatomical area is subjected to the greatest stress during the performance of holding, rotation, and hanging elements. Shoulder injuries are often the result of accumulated stress, impaired biomechanics, or insufficient muscle stabilization, which requires a structured and phased recovery strategy.

Based on the principles of progressive adaptation, neuromotor activation, and gradual return to functional activity, a four-phase rehabilitation model is proposed. It provides clearly defined goals, specific interventions for each stage, and objective criteria for moving to the next phase. This approach allows to optimize the recovery process, reduce the risk of recurrence of injury, and ensure a gradual return to full training load (Table 2).

Table 2

Rehabilitation plan for the restoration of the shoulder joint in aerial acrobatics

Phase	Objectives	Key interventions	Transition criteria
I (0–2 weeks)	↓ pain, neuromotor activation	GH and PNF blade isometries	Pain ≤ 2/10, ER strength 30 % counter-latency.
II (2–6 weeks)	Flexibility + stability	Resistance exercises on the wall, quadriceps displacements	ER ROM symmetrical, scapular dyskinesia eliminated
III (6–12 weeks)	Strengths	ER/IR expander, prone Y/T/W, boot up transfers	ER/IR ≥ 0,9
IV (12–16 weeks)	Getting back to training	Partial hanging → “skin the cat”	Painless 5× “meat hook”, tolerance до повного тренування

3. Conclusions

The shoulder girdle is a critically vulnerable area in aerial acrobatics, demonstrating the highest rates of injury among all body segments. According to epidemiological estimates, it accounts for 24% to 55% of all injuries in this sport, which is significantly higher than the corresponding figures for related disciplines such as rhythmic gymnastics (about 18%) or swimming (≈22%). This phenomenon is due to a specific load in the form of a combination of vertical traction, overhead work, and repetitive inversions. The most effective prevention strategies are programs that include eccentric strengthening of the external rotators, scapular stabilizer training, and a progressive increase in training volume (≤ 10% increase per week). It is also advisable to alternate grip techniques to minimize repetitive impact on the same anatomical structures.

From the standpoint of recovery, the proposed four-phase rehabilitation model includes the sequential restoration of range of motion, muscle strength, and functional endurance with an emphasis on the safe return to dynamic elements. The key transition criteria are achieving an ER/IR ratio of ≥ 0.9 and pain-free performance of technically demanding elements such as the meat hook.

4. Prospects for further research

At present, there are no sufficiently standardized approaches to the definition and classification of shoulder injuries in aerial acrobatics, which makes it difficult to conduct systematic reviews and meta-analyses. Future research should focus on the development and validation of clear diagnostic criteria for sports-related shoulder injuries in traction-intensive disciplines; multidisciplinary randomized clinical trials (RCTs) on the effectiveness of scapular and rotator cuff stabilization programs; and analysis of sex differences in neuromuscular adaptation and response to training stimuli, taking into account possible hormonal modulations.

An integrated approach to the study of the shoulder complex in high-performance sports will improve both clinical prevention and sports performance.

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