Innovative Conservative Treatment for Female Patients with Anterior Cruciate Ligament Injury

Zitian Wang *

College of Culinary and Food Science Engineering, Sichuan Tourism University, Chengdu, 610100, China

* Corresponding Author Email: 0000186@sctu.edu.cn

Abstract. Anterior cruciate ligament (ACL) injury is among the most common knee disorders with significant gender differences in incidence. In sports with equivalent participation, ACL injury rates are 2-8 times greater in female athletes versus males, possibly due to differences in female anatomy, physiology, and biomechanics. Despite the abundance of conservative treatment options for ACL tears, there is still a gap in the design of data plans for the unique physiological characteristics of women. Based on the gender factors affecting the mechanism of ACL injury in women, this study aims to explore a multidisciplinary framework for female anatomical, estrogenic and biomechanical characteristics in order to optimize the existing conservative treatment options, namely strengthening the hip abductor muscle, the epinephalline muscle, core stability, landing cushioning training during physical therapy, and developing rehabilitation training programs combined with menstrual periods. In addition, collagen and amino acid supplements are added to daily nutritional supplements to promote ACL recovery; It is also possible to treat ACL tears with oral contraceptives.

Keywords: Anterior cruciate ligament injury; female; difference.

1. Introduction

Anterior cruciate ligament (ACL) injuries are among the most common knee disorders, with significant gender differences in incidence. Relative to male athletes participating in comparable sports, female athletes show 2-8 times higher likelihood of ACL injury, which may be caused by the unique physiological characteristics of women, such as structural differences in physiological anatomy, sex hormone fluctuations, biomechanical differences, neuromuscular differences, etc [1]. Anatomically, due to a wider pelvis, females exhibit a larger knee varion angle during dynamic movement and a narrower femur interrecess fossa, which will augment the knee torque, resulting in greater ACL injury risk. Due to female specific sex hormone fluctuations, for example estrogen and relaxin that augment the degree of ligament relaxation, ACL injury risk is elevated in the luteal stage of the menstrual cycle. In terms of biomechanics, women's lower power ratio of corysticular muscle to quadriceps muscle and slower proprioceptive response lead to lower power dissipation efficiency in rotating or jump-landing motion tasks, resulting in more impact on ACL, thus increasing the possibility of injury.

While ACL reconstruction surgery remains a common intervention, conservative (non-surgical) treatment (which focuses primarily on functional braces, activity adjustment, and general physical therapy) is increasingly prioritising specific populations, including non-athletes, adolescents with open growth plates, and women seeking delayed surgery for personal reasons, such as pregnancy plans. However, existing conservative treatment options often do not take into account the unique biomechanical and physiological characteristics of female patients, resulting in unsatisfactory results and high recurrence rates.

Emerging evidence suggests that targeted interventions for neuromuscular control, dynamic alignment, and hormone analysis in women may enhance the effects of conservative therapy. For example, the combination of hemicardiothoracic rope strengthening, enhancement training with real-time biofeedback, and stage-based rehabilitation aligned with the menstrual cycle show promise for reducing recurrent instability. In this paper, gender specific factors affecting the mechanism of female ACL injury were discussed, and the latest advances in biomechanical research, rehabilitation science

and sex-specific medicine were integrated to explore the current optimal conservative management paradigm. By bridging the gap between pathophysiology and personalized care, this approach aims to mitigate the long-term sequelae of ACL injury in women, including articular cartilage wear, premature osteoarthritis, and limited motor function.

2. Factors Contributing to ACL Injury in females

2.1. Anatomical differences

Significant physiological structural differences exist between males and females, and different manifestations of anatomy make the risk of ACL injury different

Compared with men, female pelvis is wider, which increases the femoral patellar shear force, so there is a higher probability of posture problems (such as internal knee buckle, etc.) and knee cartilage wear. Women's wider pelvis increases the angle and moment of knee valvaration. Some studies have proved that the difference in moment during exercise may be the cause of female ACL injury,so pelvic structural differences may elevate ACL injury risk in women [2]. In addition, a wide pelvis is associated with a shortened hip abductor (gluteus medius) lever, decreased muscle efficiency, and decreased dynamic stability [3].

Intercondylar notch is the joint part of the femoral quadriceps and patella that coordinate with each other, and undertakes the function of supporting and transferring the movements of the upper and lower limbs. Women's smaller notch limited ACL activity space increases the risk of ACL impact during knee flexion, which increases the risk of ACL injury for women.

With a narrower femoral notch width, the ACL is more likely to have mechanical impact with the femur during knee flexion, extension and rotation, especially in the movement requiring sudden deceleration or direction change, such impact effect will be further amplified, thus increasing the risk of ACL injury. In addition, narrow intercondylar is often accompanied by microscopic changes such as smaller ACL volume and reduced collagen fiber arrangement density, which further weakens the tensile strength of ligaments.

The Q angle represents the angular measurement between the quadriceps muscle vector and the patellar tendon alignment. Elevated Q angles correlate with greater valgus stress at the knee, and the internal buckle (valvaration) posture is more likely to occur during dynamic movement, further increasing the risk of ACL injury [4].

2.2. Menstrual Sex Hormone Fluctuations

Menstrual periods (menstruation) are periodic changes in the lining of a woman's uterus. Since puberty, under the action of estrogen and progesterone secreted by the ovary, the endometrium has periodic exfoliation, bleeding repair and proliferation, which is called the menstrual period. The menstrual cycle includes the follicular period, the proliferative period, the menstrual period and the luteal period. In a normal menstrual cycle, estrogen gradually rises during the follicular phase, reaching a peak, and after a brief drop after ovulation, it rises again during the luteal phase. Relaxin begins to rise at the end of the follicle period and peaks at ovulation. Fluctuations in sex hormone concentrations during a woman's menstrual cycle increase the potential for ACL injury in women. Multiple investigations have reported that ACL injury likelihood in female patients is significantly increased during specific menstrual cycle phases, and the ACL injury risk reaches its maximum in women when estrogen concentrations peak around ovulation [5].

2.2.1 Estrogen changes collagen metabolism

The occurrence of female ACL injuries increases during periods of elevated estrogen levels in the menstrual cycle. Females demonstrate greater ACL injury risk during high-estrogen follicular and ovulation phases [5].

The main component of ACL is collagen, which is composed of type Ⅰ-Ⅲ collagen and other adhesive proteins, elastin, etc. Collagen molecules are arranged and combined to form collagen fibers,

which form collagen fibers, and collagen fibers combine to form fiber bundles, forming ligaments. There is a collagen fiber cross-linking structure between the collagen fibers. Lysyloxidase (LOX) is a protease that catalyzes the covalent bond between collagen and elastin, synthesized by fibroblasts, and can produce a cross-linking structure between collagen, enhancing the stiffness of ACL.

Research demonstrates that estrogen-induced metabolic changes in ACL cells may modify ligament composition, increasing injury susceptibility. At the same time, research has shown that high concentrations of estrogen can inhibit LOX enzymatic activity in human anterior cruciate ligament cells, weaken the cross-linking structure of ACL, and reduce the stiffness of ACL [6].

2.2.2 Relaxin enhances ligament relaxation

In addition to estrogen, relaxin also plays an important role in ACL damage in women. Relaxin is a relaxing polypeptide hormone, which can relax muscles and ligaments. The increase of laxin level leads to the decrease of ligament and muscle tension, so that the ligaments and tendons around the joint become relaxed, the loss of normal tension, the inability to effectively protect the joint, the increase of joint motion, resulting in a significant increase in the risk of ligament tear. Research evidence indicates peak ACL injury incidence coincides with the luteal menstrual phase, corresponding to elevated serum relaxin levels, with a demonstrated positive correlation between relaxin concentration and ACL tear frequency in female athletes [7].

2.2.3 Combined effect of estrogen and relaxin

Higher estrogen levels can lead to ligament relaxation, reduce collagen tone, and decrease the muscle tone of the rouge muscle, which heightens female ACL injury susceptibility. It has been demonstrated in cell experiments that the co-action of estrogen and relaxin can increase the expression of matrix metalloproteinase and inhibit the type I-III collagen expression in female ACL cells, while this phenomenon is not observed in males, indicating that the co-action of estrogen and relaxin is sex-specific [8].

3. Biomechanical Differences

Anatomical differences in females lead to distinct biomechanical manifestations during movement. Due to insufficient activation of the hip adductors and abductors, females tend to demonstrate enhanced hip internal rotation and adduction during activities, which increases knee valgus angles and elevates ACL loading.

In a cross-sectional study by Angela Blasimann et al., neuromuscular control was compared among three groups: ACL-reconstructed, ACL-deficient (conservative treatment), and ACL-intact individuals. The results revealed that only in the conservative treatment group did a significant gender disparity exist—female patients demonstrated approximately 30% weaker neuromuscular control than males [9]. During athletic movements, abnormal muscle activation patterns are observed in females. Relative to males, females demonstrate greater quadriceps dominance, characterized by prolonged quadriceps activation and delayed hamstring response. This imbalance increases shear forces on the knee joint, raising ACL injury risk.

As a biomechanical parameter, the H:Q ratio expresses the strength proportionality between knee flexors and extensors, calculated from their concentric peak torque values obtained through standardized isokinetic protocols, reflecting the strength balance between knee flexors and extensors. A lower H:Q ratio (H:Q < 0.6 in females) indicates elevated knee injury risk. In one investigation, researchers measured the H:Q ratios from 96 participants (50 male, 46 female) ,during knee extension and flexion in a supine position at three different angular velocities. The results showed that, regardless of torque speed and joint angle, females had a significantly lower H:Q ratio compared to males [10].

Due to this reduced H:Q ratio and weaker neuromuscular control, females exhibit reduced knee flexion and increased quadriceps muscle recruitment during landing movements, increasing stress on the ACL. Experimental studies have confirmed that, during vertical jump landings, females generate

20-30% greater knee valgus moments than males, further elevating ACL injury risk. Multiple factors—including pelvic anatomy, muscle activation patterns, and neural control—contribute to poor knee alignment during dynamic movements, reducing knee stability and increasing ACL strain.

4. Personalized Treatment Strategies for Female Patients

The conservative treatment approach following ACL injury typically includes rehabilitation therapy, functional bracing, physical therapy (such as electrical stimulation for muscle recovery), and analgesic medications. Although clinical guidelines suggest that treatment plans should account for individual anatomical differences that may affect knee joint stability post-injury, gender-specific considerations remain largely overlooked in current protocols [11].

4.1. Physical Therapy

Physical therapy can improve hip abductor weakness caused by wider pelvis through hip abductor strengthening. Initial exercises include side-lying clamshells and resistance band glute bridges with abduction to activate muscles. Intermediate training involves lateral band walks and single-leg stance with abduction to enhance strength. Advanced functional training incorporates lateral step-ups and single-leg squats with anti-rotation abduction.

Given the relative weakness of female hamstrings, closed-chain exercises should be prioritized for hamstring recruitment. Research indicates that double-leg squats result in poorer H:Q co-activation ratios compared to single-leg exercises. Specifically, single-leg training at 30-90° knee flexion optimizes H:Q ratios, ensuring adequate hamstring engagement [12].

Studies have observed that fatigue-induced reductions in hamstring reflex response and increased anterior tibial translation are more pronounced in females than males [13]. Therefore, female hamstring training programs must carefully manage workload to prevent overuse injuries.

A menstrual cycle-adapted training program should be implemented, with high-load resistance training during the follicular phase to strengthen weaker muscle groups while preventing overtraining. During the luteal phase, to minimize the effects of ligament laxity and decreased muscle tone, exercises requiring knee joint stability should be avoided and replaced with non-weight-bearing, low-impact training.

4.2. Nutritional Supplements

Adequate nutrition facilitates rapid recovery of lower limb muscle mass and strength. Studies have found that leucine supplementation is associated with increased thigh muscle mass measured 10 cm from the patella. Enhancing lower limb muscle mass and strength can protect joints [14]. Additionally, collagen and vitamin C supplementation should be considered during high estrogen phases.

Most contraceptive pills primarily consist of estrogen and progesterone, which inhibit hypothalamic secretion of gonadotropins through negative feedback, thereby reducing follicle-stimulating hormone and luteinizing hormone secretion. This suppresses follicular growth and maturation, preventing normal ovulation to achieve contraceptive effects.

Musculoskeletal (MSK) tissues are sensitive to estrogen, progesterone, and relaxin. Research has demonstrated the potential effectiveness of contraceptive pills in reducing ACL laxity and injury risk in females [15]. In a pharmacoepidemiological investigation of 13,355 women, OC use demonstrated a protective effect against surgical intervention for ACL injuries[16].

Considering female-specific hormonal fluctuations, zinc and magnesium should be increased during the luteal phase to regulate matrix metalloproteinase activity, while vitamin E supplementation during ovulation can counteract estrogen-mediated oxidative stress [17].

5. Limitation

Physical therapy may present certain challenges for female patients without exercise habits; patients opting for conservative treatment are more likely to be non-athletic populations compared to surgical patients, including elderly groups. The optimal dosage and oral absorption efficiency of nutritional supplements require further investigation. When taking contraceptive pills, potential side effects such as menstrual irregularities, headaches, and weight gain may occur, leading some women to reject their use.

Future developments could focus on creating mild hormonal medications to address estrogen-induced joint laxity in females. Integrating menstrual tracking software with PT data recording and training programs could facilitate cyclical training plans. Additionally, addressing psychosocial factors like kinesiophobia and movement confidence through cognitive behavioral strategies may improve rehabilitation adherence. Establishing patient community platforms for experience sharing could provide psychological support.

6. Conclusion

This article outlines the primary sex-specific contributors to ACL injury risk in women involve anatomical, hormonal, and biomechanical differences. It integrates current rehabilitation approaches targeting these factors, along with adjuvant nutritional supplementation. For women with contraceptive needs, oral contraceptive use may serve as a protective factor against ACL injury. However, several limitations remain, particularly regarding conclusive guidelines for exercise modification during specific menstrual cycle phases in rehabilitation.

Future research should prioritize large-scale validation studies and technological refinements to fully realize this treatment paradigm's potential. Multicenter randomized trials are urgently needed to compare traditional rehabilitation with hormone-adapted protocols, with special attention to oral contraceptive users and adolescent athletes. These efforts require coordinated funding initiatives and collaboration among clinicians, researchers, and medical device innovators to transform the current one-size-fits-all approach into truly personalized, evidence-based conservative care for female athletes.

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