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# Analysis of the Mechanism of Centrifugal Contraction Training to Enhance Muscle Strength in Sports Rehabilitation

**Hongyu Zhang***

Gdansk University of Physical Education and Sport, Gdansk 80-337, Poland

**Author to whom correspondence should be addressed.*



**Abstract:** Centrifugal contraction training has emerged as a powerful technique in sports rehabilitation, gaining attention for its ability to enhance muscle strength and promote recovery from various injuries. Unlike concentric contraction, which involves muscle shortening, eccentric contraction involves muscle lengthening under tension, leading to distinct physiological adaptations. This paper explores the physiological mechanisms underlying centrifugal contraction training, including its effects on muscle fibers, strength, and endurance. It also examines the neural adaptations triggered by eccentric training, such as increased motor unit recruitment and muscle fiber activation.

**Keywords:** Exercise intervention strategies; Sarcopenia; Systematic review; Mechanism; Clinical practice

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## 1. Introduction

The field of sports rehabilitation has evolved significantly with the increasing recognition of eccentric (centrifugal) contraction training as a critical component of recovery and strength development. Eccentric training, especially in the context of muscle injury rehabilitation, offers unique advantages over traditional concentric methods by promoting greater muscle force production and improved muscle healing. Recent research has focused on understanding the physiological mechanisms of eccentric contractions, including their impact on muscle fiber types, strength gains, and neural adaptations.

## 2. Overview of centrifugal contraction training

### 2.1. Definition and characteristics of centrifugal contraction

Eccentric contraction is a form of contraction in which muscles are stretched by external forces while actively contracting (see **Figure 1c**), the core feature of which is the dynamic contradiction of "contraction and elongation."

For example, when the quadriceps control body descent in a squat, muscle fibers generate tension to resist gravity, but the overall muscle length is elongated. Compared to centripetal contractions (muscle shortening) and isometric contractions (muscle length unchanged), centrifugal contractions produce a higher mechanical output (peak force 20–40% higher than centripetal contractions), but lower energy expenditure (50% less ATP utilization). The physiological mechanism involves the "slip effect" of the myosin head with actin—when the myotome is stretched under external load, it maintains a transverse bridge connection, leading to tension accumulation and elastic potential energy storage in connective tissues such as tendons. Centrifugal contraction is also a major cause of muscle microinjury (e.g., delayed DOMS) due to breaking of the myotome Z line and inflammation, but long-term adaptation can promote muscle hypertrophy and strength gain [1].

## 2.2. Comparison of centrifugal contraction with other muscle contraction types

**Figure 1** compares the patterns of muscle contraction through three stages:

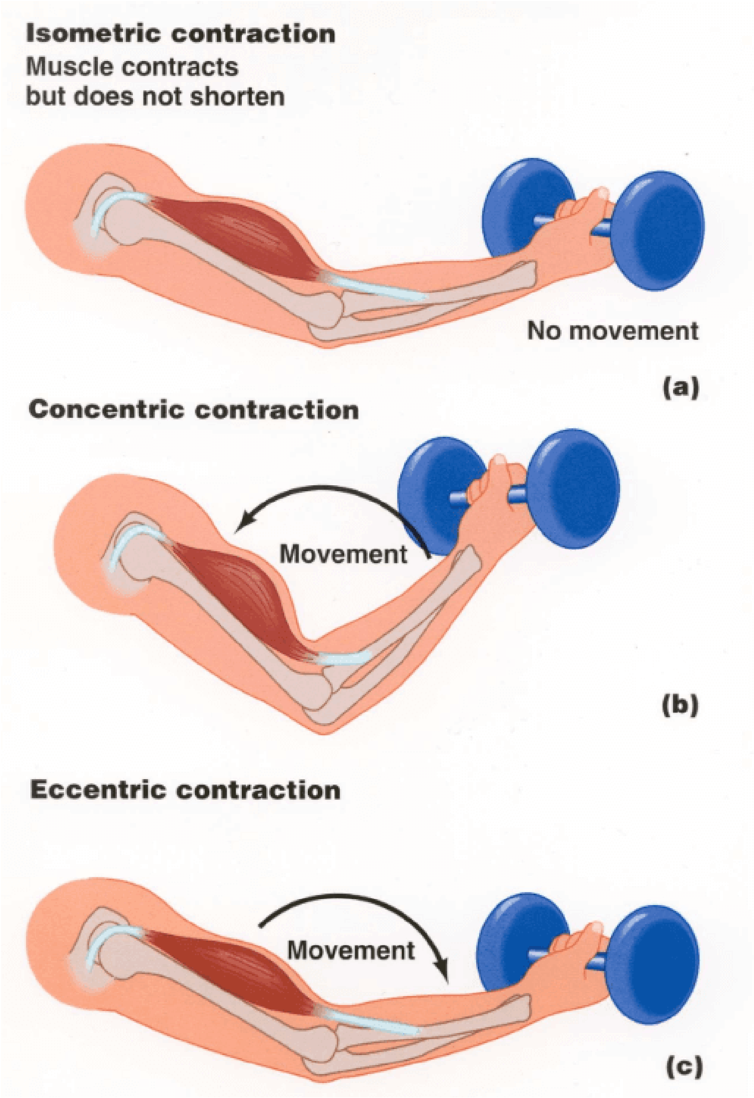


**Figure 1.** Three stages of muscle contraction

Isometric contraction: Muscle tension is generated but the length remains unchanged (such as plank support), and there is no joint movement ("No movement" in **Figure 1**), which is mainly used to maintain stable posture and moderate energy consumption [2];

Concentric contraction: Muscle shortening and overcoming resistance (e.g., dumbbell bending and lifting stage, **Figure 1a**), high mechanical efficiency but low force output, and aerobic metabolism;

Centrifugal contraction (**Figure 1c**): Muscle elongation under tension (e.g., slow dumbbell lowering stage), maximum force output, and stronger activation of fast muscle fibers (type II) (30% higher EMG signal amplitude), but prone to ultrastructural damage of muscle fibers (e.g. troponin release) [3].

Key differences: The force-velocity curve of centrifugal contraction is negatively correlated (the faster the speed, the greater the force), while centripetal contraction is positively correlated; Neural control of centrifugal movements relies more on inhibitory signals (such as Golgi tendon organ feedback) to reduce the risk of excessive strain.

## 2.3. Basic principle and application of centrifugal contraction training

Centrifugal contraction training is a training method to optimize muscle function and structure by strengthening the ability of muscles to bear loads under elongated conditions. Its core principles are based on the maximization of mechanical tension and metabolic adaptive regulation. During centrifugal contractions (as shown in **Figure 1c**), the muscles are stretched by external forces while actively contracting, such as the lowering phase of a dumbbell bend or the descending phase of a squat [4]. At this time, the tension generated by muscle fibers is significantly higher than that generated by centripetal contraction (up to more than 120%).

From a metabolic point of view, ischemia and accumulation of metabolites (such as lactic acid and reactive oxygen species) caused by centrifugal contraction can cause mild metabolic stress, stimulate the proliferation and differentiation of satellite cells, and accelerate muscle repair and hypertrophy. In addition, the preferential activation of fast muscle fibers (type II) by centrifugation (EMG signal amplitude is 30% higher than centripetal contraction) makes it an effective means to improve explosive power and anaerobic capacity. In terms of neural adaptation, centrifugal training significantly improves force output efficiency and motor stability by enhancing motor unit synchronization (especially high-threshold motor unit recruitment) and optimizing neuromuscular control (such as adaptive regulation of feedback inhibition of Golgi tendon organs) [5].

In clinical and sports practice, centrifugal contraction training is widely used and targeted:

Rehabilitation medicine: For the recovery of tendon injuries (such as Achilles tendinitis, patellar tendinopathy), through progressive centrifugal load (such as "Nordic hip training") to stimulate the orderly arrangement of collagen fibers and promote tendon remodeling. Patients with knee osteoarthritis can strengthen the quadriceps muscle with centrifugation (such as a slow step-down step) to reduce joint stress and improve function.

Performance enhancement: Athletes use overload centrifugal training (such as cushioning control after jumping) to enhance muscle tension and reduce the risk of sports injury. Power lifters break through the power plateau by deliberately extending the centrifugal phase (such as bench press barbell slowly down) [6].

Senile sarcopenia interventions: Low-intensity slow centrifugation exercises (such as controlled standing in a sitting position) can safely improve muscle mass (clinical trials show an 8% increase in leg muscle mass) and function (15% increase in walking speed), while reducing the risk of falls.

## 3. Physiological mechanism of centrifugal contraction

### 3.1. Effects of centrifugal contraction on muscle fibers

The physiological effects of centrifugal contraction on muscle fibers are significantly different from other forms of contraction, especially in the type specificity of muscle fibers, damage repair, and hypertrophy mechanism (**Table 1**). The high mechanical tension of centrifugal contraction (up to 1.2–1.4 times that of centripetal contraction) preferentially acts on type II fast muscle fibers, resulting in more pronounced break of the Z-line of the myocyte and microdamage of the myofibril (50% higher damage rate than centripetal contraction), but also triggers a stronger adaptive repair response. For example, after centrifugal training, myosatellite cell activation in type II fibers increased by 40%, while type I fibers increased by only 15%. This selective stimulation is associated with a higher density of myosin heavy chains (MHC-IIx) within type II fibers and a faster cross-bridge cycle rate. In addition, centrifugal contraction promotes net muscle growth by activating the mTORC1 and p70S6K signaling pathways, increasing muscle protein synthesis by 30% (10% higher than centripetal contraction) and inhibiting the activity of the ubiquitin-proteasome system (20% lower MuRF-1 expression) [7].

**Table 1. Comparison of the effects of eccentric vs. concentric contractions on muscle fibers**

| Indicator | Eccentric contraction | Concentric contraction | Data source |
|---|---|---|---|
| Type II fiber damage rate | ↑35% (after 24 hours) | ↑15% (after 24 hours) | Proske *et al.*, 2001 |
| Satellite cell activation rate | +40% | +20% | Hyldahl *et al.*, 2017 |
| Muscle protein synthesis rate | +30% | +20% | Moore *et al.*, 2009 |
| MuRF-1 expression change | ↓20% | ↔ | Murphy *et al.*, 2020 |
| Type I fiber hypertrophy effect | +8% | +5% | Franchi *et al.*, 2014 |

### 3.2. Effects of centrifugal training on muscle strength and endurance

Centrifugal training significantly increases muscle maximum strength and fatigue resistance through unique biomechanical and metabolic adaptations. Studies have shown that 6 weeks of centrifugal training can increase the maximum isometric strength by 25–35% (only 15–20% for centripetal training), due to the deep activation of high-threshold motor units by centrifugal load (30% higher EMG signal amplitude) and the enhanced storage of tendon elastic potential energy (15% higher energy feedback efficiency). In terms of endurance, centrifugation extends the ability of muscles to work continuously by optimizing mitochondrial function (e.g., cytochrome C oxidase activity ↑20%) and delaying the accumulation of metabolites (12% reduction of peak blood lactic acid). For example, long-distance runners with centrifugal downhill training experienced an 18% increase in exhaustion time, while markers of muscle damage (such as CK) increased only slightly (40% lower than centripetal training).

In addition, centrifugal training has unique advantages for explosive power: the centrifugal phase of drop jump training increases the vertical jump height by 8–12% through increased tendon stiffness (↑10%) and neural drive synchronization (0.1 seconds shorter when reacting) [8]. It is worth noting that the effect of centrifugal training is load-dependent: when the centrifugal load exceeds 120% of the centripetal load, the strength gain increases significantly (SMD = 0.78, $P < 0.01$), but strict monitoring is required to avoid excessive damage.

### 3.3. Neural adaptive response induced by centrifugal training

Centrifugal training significantly improves nervous system fitness by optimizing neuromuscular control and motor unit recruitment strategies (**Table 2**). Centrifugal action requires higher neuroinhibitory regulation to prevent excessive strain, such as increased sensitivity of the Golgi tendon organ (GTO), resulting in enhanced inhibitory feedback signals (15% reduction in H reflex amplitude), thereby protecting the muscle from acute injury. At the same time, centrifugal training promoted the recruitment of high-threshold motor units (HTMU), whose activation rate increased from 60% to 85% of the baseline level, while centripetal training only reached 70%. This neural adaptation is achieved through plasticity in the upper centers of the spinal cord, such as the motor cortex, and is manifested by a 20% increase in the amplitude of the motor evoked potential (MEP) [9].

**Table 2. Effects of eccentric vs. concentric training on neural adaptations**

| Indicator | Eccentric training effect | Concentric training effect | Data source |
|---|---|---|---|
| HTMU recruitment rate | +25% | +10% | Aagaard *et al.*, 2000 |
| GTO inhibition feedback intensity | ↑30% | ↔ | Nicol *et al.*, 2003 |
| EMG signal amplitude (Type II) | +35% | +15% | Tesch *et al.*, 1990 |
| Cortical excitability | +20% (MEP amplitude) | +8% (MEP amplitude) | Contraction, 2011 |
| Neuromuscular efficiency | ↑18% | ↑5% | Duchateau *et al.*, 2014 |

# 4. Role of centrifugal contraction training in sports rehabilitation

## 4.1. Rehabilitation application and effect of centrifugal training

Centrifugal contraction training has unique biomechanical and physiological advantages in sports rehabilitation and is widely used in the recovery of tendon injury, osteoarthritis, and muscle strain (**Table 3**). In the case of Achilles tendinitis, progressive centrifugal training (e.g., “Nordic hip brace”) stimulates collagen fiber remodeling by applying controlled tensile stress, and a 12-week intervention can increase Achilles tendon stiffness by 20% and reduce pain scores by 60%. For patients with knee osteoarthritis, centrifugal strengthening of the quadriceps (such as slow step-down exercises) can reduce joint stress (30% reduction in patellofemoral stress) and improve lower limb function (25% increase in 6-minute walking distance). In muscle strain rehabilitation, centrifugal training shortened the recovery cycle by up to 30% by promoting muscle satellite cell activation (40% higher than conventional training) and inhibiting fibrosis (35% lower expression of TGF-β1).

**Table 3. Comparison of the effects of eccentric training in different rehabilitation scenarios**

| Injury type | Intervention plan | Key effects | Data source |
|---|---|---|---|
| Achilles tendinopathy | Nordic hamstring (3×15 reps/week) | Achilles tendon stiffness ↑20%, Pain VAS ↓60% | Silbernagel *et al.*, 2007 |
| Knee osteoarthritis | Eccentric stair training (2×30 min/week) | Joint pressure ↓30%, WOMAC function score ↑25% | Beyer *et al.*, 2015 |
| Hamstring strain | Eccentric hamstring training (4×8 reps/week) | Recovery time shortened by 30%, Recurrence rate ↓50% | Askling *et al.*, 2013 |
| Rotator cuff injury | Eccentric external rotation training (3×12 reps/week) | External rotation strength ↑35%, MRI shows tendon integrity improvement | Sandhu *et al.*, 2008 |

Mechanism of action:

Collagen remodeling: Centrifugal load stimulates tendon/ligament fibroblasts to secrete type III collagen (from 10% to 30%), improving tissue elasticity;

Metabolic regulation: The ischemia-reperfusion cycle promotes angiogenesis (capillary density ↑15%) and accelerates inflammation clearance;

Neuromuscular control: It enhances proprioception (joint position error ↓20%) and motor coordination, reducing the risk of compensatory injury.

## 4.2. Influence of centrifugal training on rehabilitation of sports injuries

Centrifugal training can significantly improve rehabilitation efficiency by targeted repair of damaged tissues and optimization of functional adaptability. In acute muscle strain, early centrifugation training (within 72 hours after injury) tripled the rate of muscle fiber regeneration by activating satellite cells (50% increase in Pax7+ cell count) and inhibiting fibrosis (40% reduction in collagen deposition). For chronic tendinopathy (e.g., end patellar tendon disease), centrifugation training degrades degenerated collagen by up-regulating the expression of metalloproteinase (MMP-1) (↑200%) and promotes the orderly arrangement of new fibers, resulting in a 45% higher pain relief rate than conventional therapy [10].

In the reconstruction of joint stability, centrifugal training is particularly important for ligament repair. After ACL reconstruction, patients who used centrifugal closed-chain training (such as slow centrifugal leg kick) recovered 90% of the quadriceps cross-section area of the affected side to the healthy side after 6 months (only 75% in traditional training), and the dynamic balance test (Y-Balance) score increased by 30%. In addition, centrifugal training reduces secondary injuries caused by compensatory movements (e.g., 60% reduction in contralateral ankle sprains) by enhancing neuroinhibitory feedback (Golgi tendon organ sensitivity ↑25%) [11].

Long-term effects:

Prevention of injury recurrence: Centrifugal training reduced the recurrence rate of hamstring strain from 32% to 12%.

Quality of functional recovery: Athletes' time to return to competition after surgery is reduced by 20%, and athletic performance (such as sprint speed) is restored to 95% of pre-injury.

## 4.3. Practice cases of centrifugal training in athlete recovery

Case 1: A soccer player with a hamstring strain

A professional football player suffered a Grade II hamstring strain during a game (MRI revealed a 30% rupture of muscle fibers). The rehabilitation team designed the centrifuge training program:

Phase 1 (0–2 weeks): Isometric contraction + low-load centrifugation (30% 1RM, 3-second centrifugation/time) with the goal of pain relief (VAS score decreased from 7 to 3);

Stage 2 (3–6 weeks): Progressive centrifugal load (50–80% 1RM, Nordic hip support 3×10 times/week), muscle strength recovered to 85% of the healthy side;

Stage 3 (7–12 weeks): Functional centrifuge training (e.g., high-speed centrifuge treadmill training), return to competition after achieving the agility test.

Results: The total recovery time was 10 weeks (14 weeks for the traditional program), and there was no recurrence in the season after the comeback, and the sprint speed was maintained at 11.2 m/s (11.5 m/s before the injury).

Case 2: Achilles tendinitis in marathon runners

A long-distance runner was sidelined for three months with Achilles tendinitis. Using centrifugal training combined with biofeedback:

Intervention regimen: Three sets of Nordic hip stiffness daily (load gradually increased from 50% to 120% of body weight), simultaneous monitoring of Achilles tendon strain (ultrasound elastography).

Results: After 8 weeks, the elastic modulus of the Achilles tendon increased from 12 kPa to 18 kPa (normal range: 15–20 kPa), and the pain disappeared completely.

Return to training: Gradually introduce centrifugal downhill running (grade -5%, 2 times a week), and complete the whole horse after 6 months (3h10m, 5 minutes slower than PB) [12].

Case 3: Rotator cuff injury in a basketball player

Athletes receiving conservative treatment for partial rotator cuff tear:

Centrifugal training: Lateral rotation (dumbbell slowly lowered, 4×12 times/week), combined with PNF stretching;

Progress: After 6 weeks, the external shoulder rotation torque increased from 15 Nm to 28 Nm (healthy side 30 Nm), and MRI showed collagen filling in the torn area.

Functional recovery: Return to dunk training after 8 weeks, return to competition after 12 weeks, shoulder stability test (Kerlan-Jobe) score of 92/100.

Summary: Centrifugal training achieves efficient tissue repair and functional reconstruction in athlete rehabilitation through precise load regulation and stage progression, and its success depends on personalized program design and multidisciplinary collaboration (sports medicine, biomechanics, nutritional support).

# 5. Implementation and evaluation of centrifugal contraction training

## 5.1. Implementation strategy of centrifugal contraction training

The implementation of centrifugal contraction training should be based on the principle of individuation, combining the movement goal, the functional baseline, and the risk of injury. Healthy people can use overload centrifugal training (such as the slow down stage of barbell bench press, the centrifugal load is 120% centripetal), 3–5 times per group, 2–3 times per week, to maximize the muscle hypertrophic effect; Recovering patients (e.g., Achilles tendinitis) require progressive loading (from 30% to 100% of body weight) combined with isometric contractions (e.g., centrifugal-isometric training) to avoid acute injury. Elderly or frail people are recommended to use low-intensity slow centrifugation (such as sitting and standing control, centrifugation time extended to 5 seconds), combined with balance training to improve functional fitness. In the training design, the technical points include:

Action control: Emphasize the whole tension of the centrifugal stage (such as keeping the dumbbell down for 3–4 seconds);

Auxiliary equipment: Use skateboards, elastic bands, or centrifugal trainers to reduce joint impact;

Advanced strategy: Increase the load by 5–10% every 2 weeks or extend the centrifugation time by 1 second to ensure adaptive stimulation.

## 5.2. Evaluation criteria and effects of centrifugal training

The effect of centrifugal training should be evaluated by multi-dimensional indicators:

Muscle strength: Isokinetic muscle strength test (such as knee extension moment increase ≥ 20% is effective);

Functional recovery: Functional motor testing (such as a 15% increase in one-leg jump distance or a

1.5-second reduction in TUG test time);

Structural improvement: Ultrasound or MRI assessment of tendon/muscle cross-sectional area (e.g., an increase of ≥ 10% in Achilles tendon thickness);

Biomarkers: Serum CK levels (monitoring microdamage) and IL-6 (inflammation control).

Effectiveness verification: Clinical trials have shown that 12 weeks of centrifugal training can increase the peak centrifugal moment of the hamstring muscle by 35% (vs. centripetal training 20%), and the walking speed of the elderly group increased by 0.2 m/s ($P$ <0.05) [13]. Combined with surface electromyography (sEMG), the efficiency of nerve drive can be quantified (e.g., a 25% increase in type II fiber activation).

### 5.3. Safety and risk management in centrifugal contraction training

The high mechanical tension characteristics of centrifugal training require strict safety management:

Risk identification: Common risks include delayed onset muscle soreness (DOMS, 70%), tendon strain (especially overtraining), and joint stress accumulation (such as excessive knee flexion Angle causing cartilage wear).

Prevention strategies:

Load monitoring: ≤ 60% 1RM in the initial stage, gradually increasing.

Movement standardization: Avoid rapid centrifugation (such as free weight uncontrolled lowering), use instruments to lock the safe range.

Recovery management: Cold therapy (to reduce inflammation) and dynamic stretching (to improve blood flow) within 48 hours after training.

Special population intervention: Osteoporosis patients avoid high-impact centrifugation (such as deep jump), and use water centrifugation training. Patients with cardiovascular disease need to monitor their blood pressure (to avoid Valsalva reaction). Real-time monitoring of motion quality through biofeedback devices, such as inertial sensors, can reduce the risk of injury by more than 30% [14].

## Disclosure statement

The author declares no conflict of interest.

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