THE ROLE OF FOOT-ANKLE COMPLEX IN REHABILITATION AFTER ACL RECONSTRUCTION

MAKE MIRACLES HAPPEN

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INTRODUCTION

Anterior cruciate ligament (ACL) rupture is one of the most debilitating lower limb injuries an athlete can endure with significant impact on time lost from sport participation, rehabilitation's duration and the time required to return to pre-injury levels of performance[1-3]. Furthermore, this injury often carries an elevated risk of ipsilateral and contralateral injury[4], as well as an early onset of posttraumatic osteoarthritis, thereby making ALC reconstruction (ACLR) an extensively researched topic[1,2,5]. All the experts recognize the paramount importance of the quadriceps, hamstring and gluteal muscles group in enhancing functional knee stability. As a result, these muscle groups have received the lion's share of attention in the literature[6,7]. Nevertheless, the foot-ankle complex have received comparatively less focus, despite a mounting body of evidence suggesting that they can significantly influence ACLR rehabilitation outcomes, spanning from an understanding of injury mechanisms to considerations of performance enhancement[7-9].

THE FOOT-ANKLE COMPLEX AND MIR**ACL**ES

First and foremost, the foot-ankle complex should be viewed comprehensively as an intricate multi-joint structure composed of the talocrural and distal tibiofibular joints for the ankle complex and three regions of interest for the foot complex: rearfoot (subtalar joint), midfoot (medial longitudinal arch) and forefoot (metatarsophalangeal joints)[10]. Within this complex, each muscle can be categorized into three distinct group: the triceps surae (TS) and extrinsic foot muscles (EFM), both of which originate outside the foot and insert on the rearfoot, midfoot or forefoot, and finally, the intrinsic foot muscles (IFM) with both origin and insertion within the foot[10]. It is crucial to establish this clear and holistic definition in order to understand which structures (joints, muscles and tendons) are pertinent to consider during the rehabilitation process following ACLR if you want that MIRACLES happen.

Considering the significance of enhancing lower limb function after ACLR, the MIRACLES acronym has been devised to assist clinicians in enhancing the efficacy of their treatment, especially according to the lack of clarity regarding the key metrics of physical qualities related to the foot-ankle complex that should be the focal point of attention (Figure 1). Therefore, the purpose of this article is to provide a comprehensive list of the parameters associated with the foot-ankle complex that clinicians should contemplate incorporating, if necessary, periodically throughout the rehabilitation

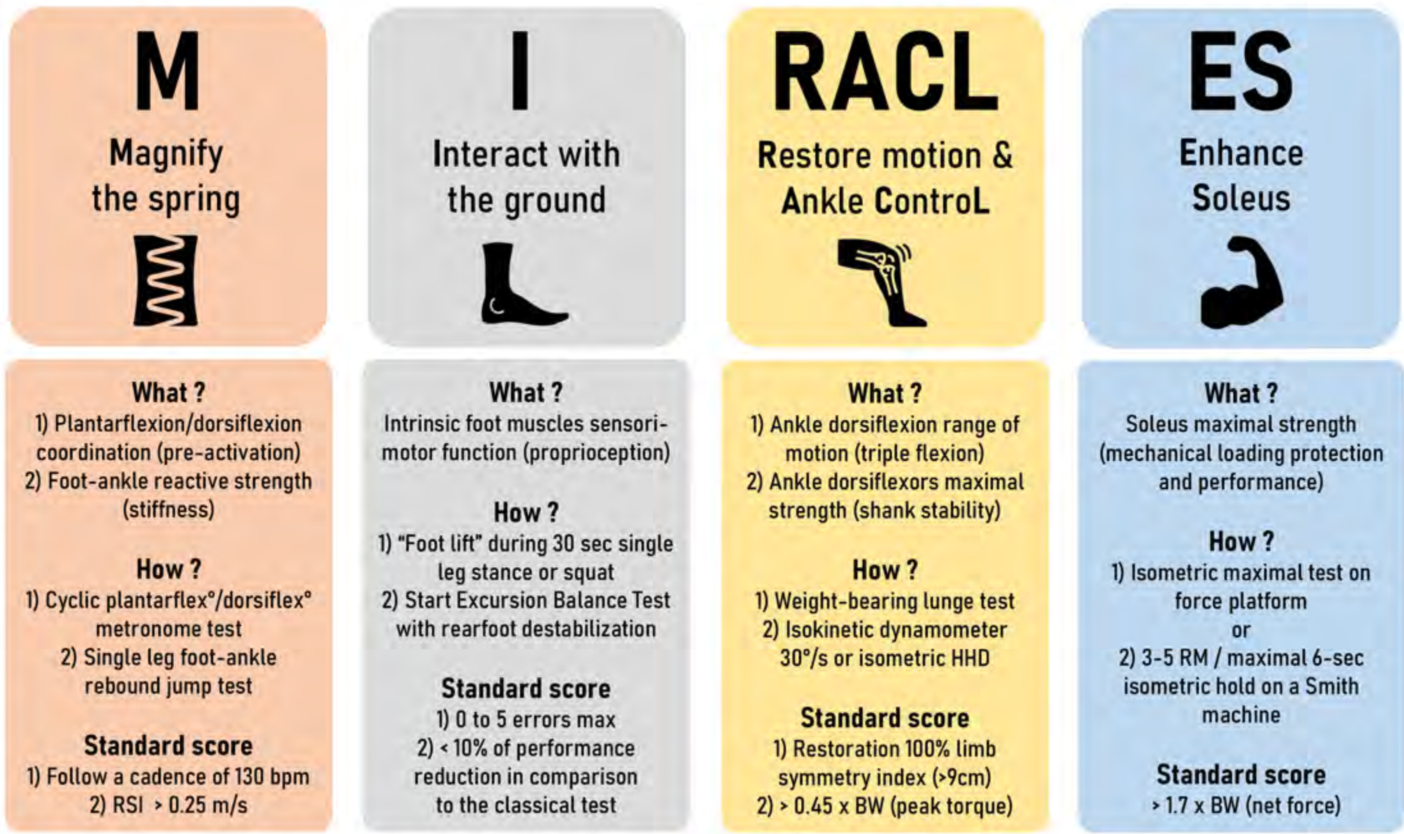

Figure 1: MIR**ACL**ES acronym=key metric related to the foot-ankle complex that clinicians should focus on throughout their rehabilitation following ACLR. BPM=beats per minute; RSI=Reactive Strength Index; HHD=Hand-Held Dynamometer; BW=Body Weight; RM=Repetition Maximum.

process for athletes following ACLR. Finally, it's important to noticed that key metrics are listed by chronological order of incorporation during the rehabilitation.

MIRACL(ES) – ENHANCE SOLEUS

Mechanical loading protection and performance

We understand that ACL injury occurs when the mechanical load imposed on the ligaments surpasses the ligament's capacity to withstand that mechanical load. This is frequently associated with sports involving jumping, pivoting or changing of direction with deceleration leading to high tri-planar load on the knee joint[6]. Given the crucial role of muscles force production in modulating mechanical load (i.e, accentuate and/or reduce), effective training of specific muscles becomes paramount in safeguarding the ACL against injury. Despite not directly crossing the knee joint, growing body of literature has highlighted that foot-ankle muscles and especially the soleus possess the greatest potential to generate ACL-protective posterior shear forces during unanticipated sidestep cutting and single leg drop landing[7,14,15]. As soleus is a key ACL agonist along with the hamstrings, strategies aimed at enhancing its maximal strength should be promoted. This becomes even more crucial with athletes who have undergone hamstrings graft (gracilis/semitendinosis) since studies have indicated that strength deficits are exacerbated by graft selection post-surgery[16]. In addition to its protective function, the soleus also provides the majority of vertical support and acceleration of the center of mass of the lower limb muscles and additionally contributes (following the gastrocnemius) to the propulsive acceleration during sprinting and cutting[17,18].

Rehabilitation recommendations

While we acknowledge that the soleus is the primary force contributor around the talocrural joint due to its specific architectural features designed for maximal force production[19-21] it doesn't necessarily imply that it is "strong" in every athlete. Interestingly, previous studies have revealed a significant reduction in its contribution in both legs of athletes after ACLR during horizontal and vertical jumping[9,22], potentially affecting force production during the second half of the propulsion phase[23]. This could be attributed to the development of kinetic chain deficits throughout the leg segment following the immobilization/protection for the injured knee. Hence, for protective and performance considerations, assessing soleus maximal strength capacity in isolation and training it if necessary after ACLR should be the first MIRACLES key metric. We propose that this evaluation should be conducted using a force platform with a 90° hip and knee angle and a foot-ankle in neutral position for standardization, according to the potential influence of varying body positions on force generation[24] (Figure 2a). In this setting, we aim for net peak isometric force values of ~1.7 x BW as a standard for every multidirectional athlete post-ACLR. In cases where a force platform is unavailable in your clinical setting, you can consider alternative methods such as performing 3-5RM or a maximal 6-sec isometric hold on a Smith machine. Using a clinical reasoning, if the net peak force mentioned above falls below the threshold values, it is advisable to incorporate soleus maximal strength training into the rehabilitation process. This

Figure 2: Enhance Soleus: 1st foot-ankle key metric following ACLR. (a) Soleus maximal strength evaluation on force platform; (b) Soleus strengthening using seated calf raise exercise on reverse leg curl machine.

can be achieved using preferentially seated calf raise exercises with heavy weight machine (eg. Smith machine, reverse leg curl machine) (Figure 2b).

We then recommend three key considerations for your programming:

- Initiating the development of soleus strength when the knee can be flexed at more than 90°. This can be started early and safely for the majority of athletes using isometric exercises (don't waste your time).
- Developing endurance capacity during the first two months after ACLR using multiple repetitions with loads around bodyweight and then developing maximal strength with concentric-eccentric exercises and/or supramaximal eccentric exercises until you reach your target threshold is a valuable progressive option (don't be shy).
- Applying training hypertrophy principles (high volume, repetitions to failure, exercise specific prescription, nutrition…) in case of calf atrophy following surgery will prevent from long term strength deficits (don't forget addressing the structural component).

MI(RACL)ES: RESTORE MOTION AND ANKLE CONTROL

Dorsiflexion and shank stability

The sagittal plane range of motion (ROM) and control are crucial aspects to restore following ACLR because lower limb joints work together (i.e. triple flexion) to attenuate landing forces during landing, cutting or running[25]. Moreover, there has been a consistent observation of sagittal plane kinetics and kinematics differences between individuals who subsequently suffer ipsilateral and contralateral ACL injuries, emphasizing the importance of focusing on this plane during rehabilitation[4,26]. While restoring knee mobility is a well-established post-surgery criterion, less attention has been given to the ankle mobility, particularly dorsiflexion ROM. Reduced ankle dorsiflexion limits the ability to fully flex the knee during weight bearing, resulting in increased knee-valgus displacement and higher peak ground reaction forces (GRF) during landing[25,27,28]. This suggests that reduced ankle dorsiflexion affects force absorption capacity and may lead to increased ACL loading due to frontal-plane compensations. This becomes even more critical when dealing with athletes who have chronic ankle instability (CAI), a condition known to be associated with ankle dorsiflexion deficit (as mentioned earlier)[29,30], and the Cumberland Ankle Instability Tool displaying a score ≤24 points[31]. Beyond injury risk reduction, sagittal plane ankle motion clearance also impacts athletic performance. Athletes with greater ankle dorsiflexion angles (i.e. triple flexion) are capable of more rapid deceleration during intense cutting tasks, enabling them to dynamically lower their center of mass position when braking[32]. In addition, aside from ROM, having adequate control over the shank's movement in the sagittal plane is critical for both injury prevention (anterior tibial translation) and performance optimization. Factors such as shank orientation, stability, and discipline will determine braking GRF magnitude during deceleration[32,33] and the ratio of forces during acceleration[34].

Rehabilitation recommendations

While the soleus takes the spotlight in the shank segment, it's crucial not to overlook its antagonist, the dorsiflexor muscles, because their co-contraction plays a pivotal role in ensuring shank stability[35], and controlling foot-ankle position and pre-tension before ground contact (as discussed earlier). Therefore, ankle dorsiflexion ROM and dorsiflexors maximal strength should be considered as the second and third MIRACLES key metric. Although the weight-bearing lunge test is commonly regarded as the gold standard for evaluating ankle dorsiflexion ROM (Figure 3a), it's essential to individualize treatment strategies rather than adopting a "one size fits all approach". In case of an anterior blocking feeling, we recommend employing manual glide therapy on talus bone if the "posterior talar glide test" yields positive results[36,37]. Conversely, if the test is negative, consider utilizing manual glide therapy on the distal tibiofibular joint or midfoot joint[38]. When a postero-medial blocking sensation is detected, the treatment should focus on weight-bearing dorsiflexion with 1st ray in dorsiflexed position to enhance flexor

Figure 3: Restore motion and Ankle ControL: 2nd and 3rd foot-ankle key metric following ACLR. (a) Weight-bearing lunge test; (b) Flexor hallucis longus flexibility gain exercise; (c) Ankle dorsiflexors maximal peak torque evaluation on isokinetic dynamometer at 30°/s; (d) Ankle dorsiflexors maximal isometric strength evaluation using a hand-held dynamometer.

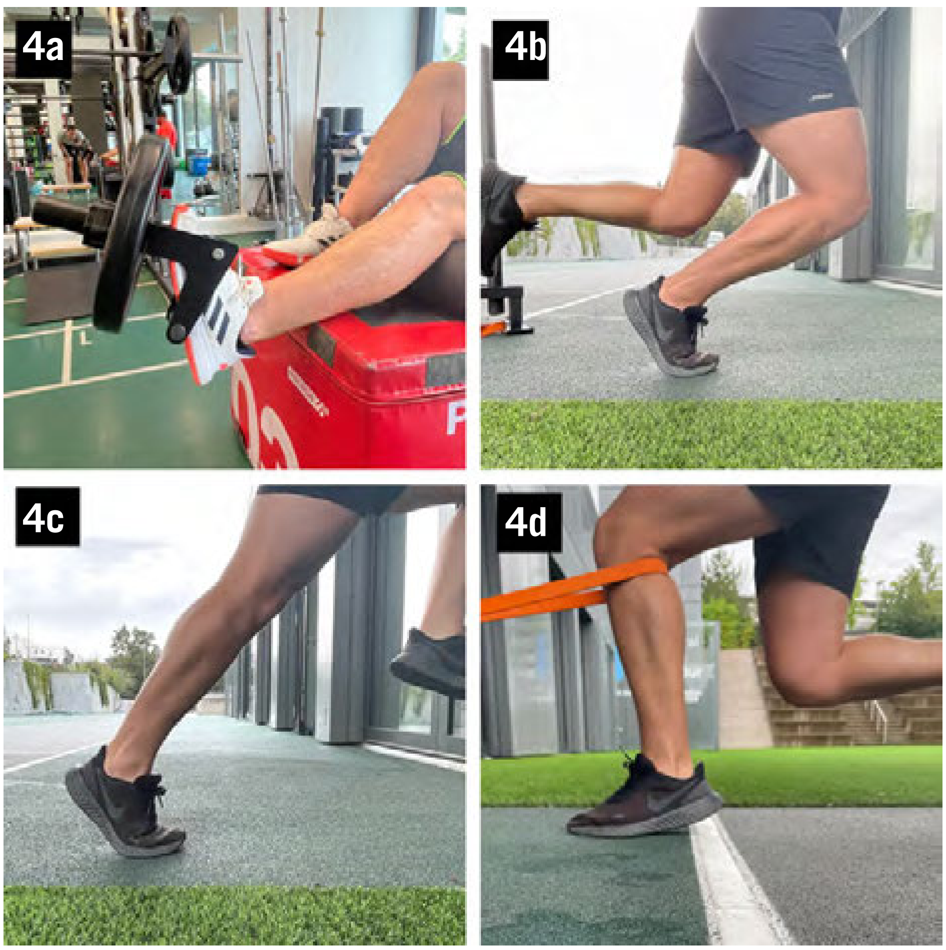

Figure 4: Restore motion and Ankle ControL: 2nd and 3rd foot-ankle key metric following ACLR. (a) Ankle dorsiflexors strengthening using heavy-weight exercise with ankle shin-bar; (b & c) Shank discipline during wall drills isometric exercises (acceleration focus); (d) Shank discipline during braking step exercise (deceleration focus).

hallux longus flexibility[39] (Figure 3b). Lastly, specific ankle plantarflexors stretching techniques or neurodynamics mobilization of the tibial nerve should be employed in athletes experiencing a posterior blocking sensation[40,41]. These techniques aim to restore dorsiflexion ROM to achieve a limb symmetry index of 100% and a minimal distance from the toe to wall of 9 cm. Secondly, we propose that the ankle dorsiflexors maximal strength evaluation should be conducted in prone position, knee extended, using an isokinetic dynamometer at contraction velocity of 30°/s[42]; or if not available, an HHD (hand-held dynamometer) can be used in a supine position with foot-ankle in neutral position (Figure 3c,d).

In this setting, we aim for isokinetic peak torque ~0.45 x BW and ~0.40 x BW for HHD as the standard for athletes post-ACLR. If necessary, we recommend incorporating strength training for dorsiflexors using heavy weight exercises with an ankle shin-bar (Figure 4a), as elastic bands may not provide sufficient resistance for these muscles. To ensure the full utilization of available dorsiflexion ROM, trunk flexion and knee extension should be minimized to reduce posterior chain (neural and muscular) stretching during the exercise. Thirdly, we suggest integrating a more functional approach by emphasizing shank stability for acceleration focus (i.e. isometric wall drills) and/or deceleration focus (i.e. braking step) (Figure 4b,c,d). During these exercises, capturing slow-motion video recordings to visualize shank motion and coaching technical errors can be immensely beneficial.

M(I)RACLES: INTERACT WITH THE GROUND

Intrinsic foot muscles ground informants

Postural control is defined as the ability to monitor body position and alignment in space, involving multimodal interactions of the sensorimotor system[43]. It has been shown to decrease after ALCR in several axes (anteroposterior, mediolateral)[44,45]. In parallel, an overreliance on visual information compared to proprioceptive signals has been reported in injured subjects[46]. It has been hypothesized that this is the result of damage to ligament mechanoreceptors, leading to a disruption in sensory transmission. This reduces the adaptability and efficiency of the central nervous system to use, integrate and reweight the various sensory inputs (i.e. vestibular, visual and proprioceptive) dynamically according to the sporting context[47,48]. As the only interface with the ground, the foot complex is strategically positioned to provide immediate sensory information through plantar cutaneous receptors and IFM activity[49,50]. IFM are considered the primary source of proprioception and play a critical role in the lower limb chain, thanks to their higher density of muscle spindles compared to others muscles[51]. In single legged stance, mediolateral postural sway has been found to correlate with IFM activity, underscoring their contribution through the foot-ankle complex to control postural balance in frontal plane by maintaining contact with the forefoot region and the ground[49,52]. Therefore, the ability of the central nervous system to use and integrate reliable sensory information rising from the IFM muscles is crucial. This becomes even more critical in athletes who have undergone both ACLR and suffer from CAI, as this bilateral loss of mechano receptor-mediated afferent feedback could lead to substantial postural balance deficits and increased reliance on visual cues[46,53].

Rehabilitation recommendations

Foot stability can be viewed as a complex neuromuscular process that encompasses both afferent and efferent signals from foot muscles, with a significant role played by IFM in enhancing postural control. Consequently, evaluating IFM sensorimotor capacities and targeted training, when necessary, following ACLR should be the fourth MIRACLES key metric. Given the inherent difficulty in directly assessing IFM, we firstly propose to evaluate this metric by assessing the numbers of "foot lift" (toes or metatarsal heads lifting from the floor) during a standardized static postural task such as 30 seconds single leg stance with eyes closed[54] or a functional postural task like a repeated single leg squat. Secondly, we recommend modifying the Star Excursion Balance Test by introducing a destabilization device (i.e. tennis ball, half sphere cone) under the rearfoot to increase forefoot proprioceptive reliance during this task[55]. You can then compare posteromedial and posterolateral normalized reached distances to those in the standard version. During these evaluations, achieving 0 to 5 maximal lift during postural tasks and experiencing a performance reduction of less than 10% for each posterior direction (as the MDC ≈ 7.70%)[56] when adding rearfoot destabilization can serve as an indicator of effective forefoot interaction with the ground. To rapidly enhance IFM activity and forefoot strength, we propose using IFM neuromuscular electrical stimulation (NMES) sessions, with electrodes placed under the arch (Figure 5a) in conjunction with maximal isometric MTPj flexion exercises in tilt dorsiflexed position with body-overloading[52] (Figure 5b). Interestingly, IFM' NMES sessions could be initiated early in the rehabilitation process, as they only require weight-bearing status. Finally, we advocate for integrating a more functional approach by incorporating postural control exercises that involve destabilization devices placed under one specific region of the foot (rearfoot, forefoot or midfoot) while allowing others parts to interact with the ground and generate GRF to maintain balance (Figure 5c,d).

Figure 5: Interact with the ground: 4th foot-ankle key metric following ACLR. (a) Placement of the NMES' electrodes under the medial longitudinal arch; (b) Forefoot strengthening using maximal isometric MTPj flexion exercise in tilt dorsiflexed position with body-overloading; (c) Static postural control exercise with rearfoot destabilization device; (d) Dynamic postural control exercise with rearfoot destabilization device.

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Altering also the stiffness (foam to firm) of the destabilization devices might be also a good way to challenge foot versality and proprioceptive cues rising from IFM.

(M)IRACLES: MAGNIFY THE SPRING

Springy foot-ankle complex

Lower limb reactive strength deficits are often persistent and tend to recover slowly during post ACLR rehabilitation[23,57]. Quantifying reactive strength performance (e.g. vertical drop jump test) can provide insights into an athlete's ability to efficiently utilize the stretch- shortening cycle (SSC) during high eccentric stretch load, like landing or changing direction[58]. The athlete's capacity to absorb efficiently GRF by reducing landing impact is a crucial aspect following ACLR and this could be enhanced by the foot-ankle complex, which plays a significant role in energy absorption during small to medium-height jump landings (0-30cm)[59–61]. Furthermore, adopting a midfoot/forefoot landing technique has been demonstrated to reduce knee valgus and tibial internal rotation knee moment during both landing[62] and cutting[63,64], thus mitigating potential ACL excessive stress loading thanks to efficient "springy foot-ankle complex". Therefore, a higher level of pre-activation and co-contraction of foot-ankle complex muscles prior to ground contact appears crucial for dissipating energy, enhancing SSC and consequently protecting the ACL, given that ACL injuries commonly occur within the first 40ms post ground contact. This level of stiffness of foot-ankle complex before ground contact depends not only on the plantarflexors (triceps surae, EFM toe flexors, in coordination with IFM) but also on the coordination with dorsiflexors (EFM). Indeed, dorsiflexed toes and ankle positioning before ground contact allow isometric elastic muscle action and greater elastic energy storage in the Achilles tendon and medial longitudinal arch[65].

Rehabilitation recommendations

As plyometric training is a well-established component of the ACLR rehabilitation process[58,66] it's essential to consider some often-overlooked foundations as achieving a "springy foot-ankle complex" doesn't simply mean having athletes bounce quickly. Therefore, coordination of foot-ankle plantarflexors and dorsiflexors, as well as specific plyometrics to enhance foot-ankle stiffness, should be the last of the MIRACLES key metrics. First we recommend evaluating coordination by assessing an athlete's ability to perform rapid cyclic foot-ankle plantarflexion/dorsiflexion while standing, following a metronome cadence set at 130 bpm. If necessary, this plantarflexion/ dorsiflexion coordination can be trained by using the evaluation setting but at a slower beat. Once this foundation is established, dynamic "penguin marches" exercises with varying rhythms can be incorporated, ensuring that motion originates solely from the talocrural joint without lower-limb flexion compensation (Figure 6a). In parallel to this basic foundation before starting plyometrics, we secondly propose to evaluate foot-ankle reactive strength and SSC capacities using single leg "foot-ankle rebound jumps"[65,67] (Figure 6b). In this vertical jump, athletes aim to jump "as high as possible and as quickly as possible" while keeping their lower limbs fully extended and pushing against the ground with only ankle plantarflexion and MTPj involvement during eight jumps. Using a force platform or optoelectronic system, assess the mean reactive strength index (jump height / ground contact time) of four jumps (excluding the first and last two) while ensuring that knee was extended. We aim for a reactive strength index of 0.25 m/s as a standard for good foot-ankle stiffness capacity. If deficit is present, plyometric training should incorporate multi-directional pogo jumps with the intention for athletes to "bounce fast and springy" while having the foot-ankle in neutral position before ground contact. Additionally, athletes should slightly bend their knees during the collision with forefoot/midfoot contact, avoiding heel collapse, which helps reduce forward knee translation. Finally, to enhance energy storage and release within foot-ankle tendon structures and improve foot-ankle versatility, consider performing pogo jumps on an everted inclined plate and vary surface stiffness[68,69] (Figure 6c).

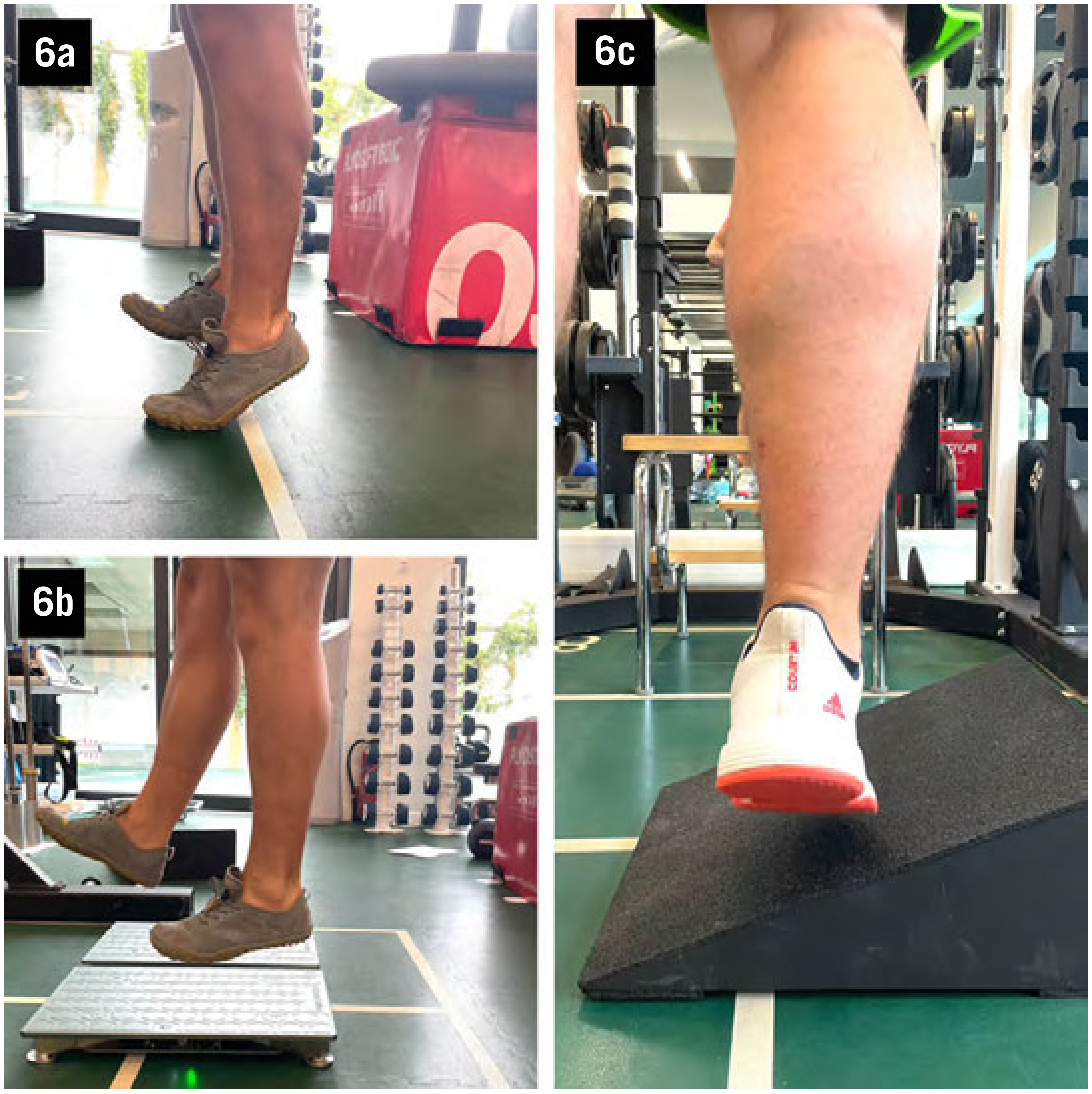

Figure 6: Magnify the spring: 5th foot-ankle key metric following ACLR. (a) Foot-ankle plantarflexion/dorsiflexion coordination test using metronome beat; (b) Single leg foot-ankle rebound jump test on force platform; (c) Single leg pogo jumps on everted inclined plate to increase foot-ankle energy storage and release.

CONCLUSION

In this article, we have demonstrated that the foot-ankle complex can meaningfully impact post-ACLR rehabilitation, from both an injury prevention and performance enhancement perspective. We hope that clinicians will take into account each of the MIRACLES key metrics of physical qualities in their programming, as we are confident that these various physical qualities (strength, proprioception, reactive strength, coordination) related to the foot-ankle complex can enhance the effectiveness of their rehabilitation strategies for athletes following ACLR.

References
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