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**Strength and power training in rehabilitation:
Underpinning principles and practical strategies to return athletes to high performance**

Short title:

Strength and power training in rehabilitation

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ABSTRACT

Injuries have a detrimental impact on team and individual athletic performance. Deficits in maximal strength, rate of force development (RFD), and reactive strength are commonly reported following several musculoskeletal injuries. This article first examines the available literature to identify common deficits in fundamental physical qualities following injury, specifically strength, rate of force development and reactive strength. Secondly, evidence based strategies to target a resolution of these residual deficits will be discussed in order to reduce the risk of future injury. Examples to enhance practical application and training programmes have also been provided to show how these can be addressed.

KEY POINTS:

- Residual deficits in maximal strength, rate of force development and reactive strength are documented following musculoskeletal injury
- Targeting these residual deficits following injury can reduce the risk of future injury as a means of tertiary prevention
- Rehabilitation should prepare athletic populations to tolerate loads and velocities across the full spectrum of the Force-Velocity curve and this is essential for returning injured athletes to high performance levels

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59

60 **1.0 Introduction**

61 Injuries have a detrimental impact on team and individual athletic performance, with
62 increased player availability improving the chances of success [1]. The available data suggest
63 an interaction between injury, performance, physical outputs, and success at both a team and
64 individual level [2-4]. It seems logical that all staff involved should strive to work together in
65 an interdisciplinary fashion to prevent injuries and to improve performance. Furthermore,
66 several studies have reported that a previous injury may increase the risk for subsequent
67 injuries [5-10]. This raises the question of whether persistent deficits have been fully assessed
68 and targeted before athletes return to play (RTP), and if a greater emphasis should be placed
69 on a return to performance strategy as a means of tertiary prevention[11].

70 Following the occurrence of injury or pain onset, deficits in strength [12-16], strength
71 ratios [17], rate of force development [18-23], reactive strength [24-26], leg stiffness [27-31],
72 and peak power [32-34], have all been shown in athletic populations. Equally, these same
73 attributes are widely considered important physical performance determinants in high
74 performance sport [35, 36]. In spite of this, rehabilitation programmes often adopted in
75 research and clinical practice are mainly focused on restoring strength [37-40], which by
76 definition, consists of high forces at low velocities. However, this alone may not fully prepare
77 the musculoskeletal system to accept and produce moderate to high loads at rapid velocities,
78 which underpin most sporting actions. Furthermore, maximal strength and ballistic power
79 training (which is typically advocated for the latter) induce different physiological
80 adaptations. There is, however, a strong interplay and overlap in both performance and
81 physiological determinants between maximal strength development and ballistic power
82 training. Maximal strength serves as the foundation for the expression of high power outputs,
83 making the adoption of training with heavy loads advantageous, not only for relatively
84 weaker athletes, but also for improving physiological features necessary for high velocity
85 actions [41, 42]. Strength training with heavy loads (i.e., $\geq 80\%$ one repetition maximum
86 (1RM)) increases neural drive, intermuscular coordination, myofibrillar cross-sectional area
87 (CSA) of Type II fibers, lean muscle mass, and pennation angle [43, 44]. Ballistic power
88 training is more specific in increasing maximal power output, rate of force development
89 (RFD), movement velocity, jump height and sprint performance via lowered motor unit

90 recruitment thresholds, improved motor unit firing frequency, and synchronization, as well as
91 enhanced intermuscular coordination [43, 45]. These positive physiological and performance
92 changes are relevant from both a rehabilitative as well as performance perspective and should
93 lead towards a unified vision that encompasses robustness and resilience for enhanced
94 performance and reduced risk of re-/ subsequent injury.

95 This article will examine the available literature pertaining to strength and power
96 development to provide a theoretical framework, from which, clear strategies are developed
97 to indicate how these principles and training modes can be incorporated into rehabilitation,
98 optimizing the return to play and return to performance process. The aim of this article is to
99 give clinicians guidance with clear practical applications to assist with resolving persistent
100 deficits that may be present in athletic populations following injury. This information is
101 important as it will enhance sports performance and reduce the risk of recurrence and
102 subsequent injury.

103

104 **2.0 Maximal Strength**

105 The development of muscular strength can be broadly divided into morphological and
106 neural factors [46]. The maximal force generated by a single muscle fibre is directly
107 proportional to its cross-sectional area (CSA) [47, 48] which is determined by the number of
108 sarcomeres in parallel, an important parameter of its force generating capacity. Greater
109 pennation angles are more common in hypertrophied than in normal muscles. Maximal force
110 is also influenced by the muscle fibres composition [44, 46, 49, 50]. Specifically, type II
111 fibres (IIa/IIx) have a greater capacity to generate power per unit CSA, than the relatively
112 smaller type I fibres. Architectural features such longer fascicle length allow more force
113 production through an optimal length-tension relationship [46]. The number of sarcomeres in
114 series influences a muscle's contractility and the rate at which it can shorten. In regards to
115 neural factors, the size principle dictates that motor unit (MU) recruitment is related to motor
116 unit type and that MUs are recruited in a sequenced manner based on their size (smallest to
117 largest) [51]. Thus, the availability of high-threshold MUs and/or lower threshold of MU
118 recruitment is advantageous for higher force production. Furthermore, a higher rate of neural
119 impulses (firing frequency) and the concurrent activation of multiple motor units (motor unit
120 synchronization) enhance the magnitude of force generated during a contraction. These,
121 together with an effective inter-muscular coordination (i.e. appropriate magnitude and timing

122 of activation of agonist, synergist and antagonist muscles) permit maximal force production
123 [44, 46, 49, 50, 52].

124

125 ***2.1 The importance of maximal strength***

126 In sport, the ability to generate maximal force is limited by the time constraints of
127 specific tasks; thus, rate of force development (RFD) and power, are a critical part of
128 optimising physical performance. Maximal strength can be defined as the upper limit of the
129 neuromuscular system to produce force [53], with increases in this capacity correlated with
130 RFD and power [45, 54-56]. Current literature suggests that athletes who can back squat 2 x
131 body mass are able to best capitalise on these associations [55], as well as changes in
132 endocrine concentrations (namely testosterone) in response to training [57]. Furthermore,
133 current evidence suggests that until athletes can squat at least 1.6 x body mass, maximal
134 strength training should be the dominant training modality [43]. Specifically, Cormie et al.
135 [43] examined the effect of a 10-week (3/week) training intervention of either strength
136 training or ballistic-power training on jumping and sprinting performances, force-velocity
137 profile, muscle architecture, and neural drive in a cohort of 24 male subjects who were
138 proficient in the back squat. They found that despite both groups displaying similar
139 improvements in performance, relatively weak men (back squat < 1.6 x BM) benefited more
140 from strength training due to its potential long-term improvement. This occurred as a result of
141 increased neural activation and muscle thickness, which are adaptations specific to this type
142 of training stimulus. This is in line with the recent research performed by Comfort et al. [58]
143 who showed that prior identification of athletic physical characteristics (here using the
144 dynamic strength index calculation) may improve the prediction of significant changes in
145 response to a specific type of training. In particular, they emphasized the importance of
146 increasing force production via strength training in weaker athletes. This is reinforced by
147 James et al. [59], who revealed that the magnitude of improvement in peak velocity in
148 response to ballistic training was significantly influenced by baseline strength levels in the
149 first 5 weeks of training. Overall, the available evidence suggests that achieving and
150 maintaining a high level of strength is of utmost importance in the athletic population for
151 positive adaptations.

152 Indeed, developing maximal strength has been shown to have significant benefits on
153 musculotendinous stiffness [60], neuromuscular inhibition [44, 61], and connective tissue

154 strength [62-65], culminating in decreases in the relative force (% of maximum) applied
155 during the loading phase of running at ground contact [66-68]. Collectively this reduces
156 metabolic demand for the same force output, creating a motor unit reserve available for
157 additional work [67]. Normative data to ensure when a patient or an athlete is “strong
158 enough” are available for isometric bilateral adductor strength tests [5, 13], although
159 strength ratios between muscle groups of the same limb [17, 69] or threshold for inter-limb
160 asymmetries are more commonly reported [12, 70-75]. These values may be used to examine
161 single joint strength and guide training programs, and to determine readiness to return to play
162 following injuries; however, global measures of maximal strength are also warranted which
163 display heightened transfer to athletic performance.

164 In addition to the physiological and performance advantages of developing maximal
165 strength, it is not surprising that injury risk may be reduced by the adoption of this training
166 modality. Lauersen et al. [76] indicated that a variety of strength training modalities can
167 reduce sports injuries by one third, and overuse injuries by almost half. Furthermore, strength
168 training programmes appears superior to neuromuscular training and multicomponent
169 programmes in injury reduction [76] . More recently, Malone et al. [77], have shown that
170 over two consecutive seasons, athletes who are stronger, faster, and have better repeated
171 sprint ability (RSA) times, have a lower injury risk than their weaker counterparts. Thus,
172 increasing strength is a key component of any tertiary prevention approach and should be
173 targeted within injury rehabilitation to reduce the risk of re-injury[11]. However, while
174 research and clinical practice promote increases in strength, this has been largely investigated
175 in several injury types in isolation, often with much lighter loads and subsequently higher
176 repetition ranges. For example, loading schemes of < 80% 1RM are often reported in
177 research articles with a rep-set configuration of “15x3” or “10x3” without a clear indication
178 of the load employed [78, 79], or by using relatively low loads, thus not targeting higher
179 threshold motor units to maximise strength adaptations [80-83]. Instead, the clarity in details
180 of exercise prescription is fundamental to define the physical as well as athletic adaptations
181 targeted.

182 ***2.2 Strength deficits following injury***

183 Increased inhibitory inputs may reduce the extent to which muscles are voluntarily
184 activated[84]. It is widely acknowledged that in the acute phase after an injury, local
185 phenomena occurring in peripheral tissues such as swelling, inflammation and joint laxity,

186 may change the discharge of sensory receptors, which causes neuromuscular inhibition. This
187 is often referred to as arthrogenic muscle inhibition after distension or damage to structures
188 of a joint [85]. Neuromuscular inhibition can persist even in absence of effusion or pain [86],
189 leading to persistent strength deficits that impair normal physical function, return to full
190 performance, and increase the risk of re-injury and subsequent injury [87]. Mechanisms for
191 this inhibition include complex neural adaptations from spinal reflex (affecting the group I
192 non-reciprocal (Ib) inhibitory pathway, the flexion reflex and the gamma loop) and
193 corticomotor excitability pathways [86, 88-90]. Neuromuscular inhibition would therefore
194 explain persistent neuromuscular alterations (e.g. shift in joint-torque angle relationship,
195 atrophy, reduction in in-series sarcomeres) and limit positive muscle adaptations to training
196 despite the return to play [91-94].

197 Knee extensor and flexor strength is significantly reduced after anterior cruciate
198 ligament reconstruction (ACLR) [16], even up to 10 years post-surgery [95]. These measures
199 have been used to guide rehabilitation status [32] and reported as a significant predictor of re-
200 injury [70]. Similarly, several studies have indicated that lower levels of eccentric knee flexor
201 strength increased the risk of hamstrings re-injury [12]. This may be due to the directional
202 specificity of the hamstring complex or this persistent maladaptive feature not being
203 completely resolved in previously injured players. In fact, Brughelli et al. [96] showed that
204 Australian Rules Football players with previous hamstring injuries had significant deficits in
205 horizontal but not vertical force during running at submaximal velocities. Similarly, Lord et
206 al. [97] demonstrated that horizontal force production decreases at a greater rate in previously
207 injured than uninjured hamstrings during an RSA test in football players. Charlton et al. [98]
208 found isometric knee flexion strength deficits in semi-professional Australian Rules Football
209 players with a past history of hamstring injury for up to three seasons following injury. Other
210 studies investigating common lower limb injuries revealed discrepancies in the association
211 between strength values and risk of injury [32, 99] as well as inconsistent patterns of strength
212 and performance change in symptomatic and asymptomatic subjects [100]. In addition,
213 research has shown that muscle strength is impaired bilaterally and below normative data in
214 runners with Achilles tendinopathy [101].

215 ***2.3 Using maximal strength training to target deficits***

216 The available data suggest higher strength levels help reduce the risk of sports injuries
217 [12, 102, 103]. From a rehabilitation perspective, patients should be gradually progressed to

218 heavier loads in a periodized manner, with high-intensity resistance training being a valid and
219 effective therapeutic tool across age and gender in the treatment of the most common
220 musculoskeletal injuries [104, 105]. From a neurobiological perspective, it may also reverse
221 alterations in intra-cortical inhibitory networks in individuals with persistent musculoskeletal
222 pain [88, 89, 100].

223 Current evidence indicates that prescription of maximal strength training should
224 involve a load (or intensity) of 80-100% of the participant's one-repetition maximum (1-
225 RM), utilizing approximately 1-6 repetitions, across 3-5 sets, with rest periods of 3-5 minutes
226 and a frequency of 2-3 times per week [106]. Hence, for clinicians whose specific aim at a
227 particular phase is to improve maximal force, they should be progressively working toward
228 this volume load prescription. Evidence-based recommendations for an effective stimulus for
229 tendon adaptation suggest high intensity loading (85–90% iMVC) applied in five sets of four
230 repetitions with a contraction and relaxation duration of 3 s each and an inter-set rest of 2min
231 [107]. However, in the initial stages when they are unable to tolerate heavy loads, lower
232 intensities may be employed in multiple high volume sets until momentary failure, in order to
233 recruit the highest threshold motor units and to increase CSA [108, 109]. Alternatively, blood
234 flow restriction training can be used to provide an effective stimulus during rehabilitation for
235 patients who are load compromised [110]. Cross-education (i.e. heavy resistance training of
236 the unaffected limb) can be also a viable option to reduce corticospinal inhibition [111], to
237 increase contralateral limb strength [112] and to induce hypoalgesia [113]. A potential
238 progression based on the rehabilitation phase and the patient's irritability post ACLR might
239 be: 1) bodyweight single leg squat performed at high volume sets focusing on technique
240 mastery and cross-education 2) single leg squat with light load and high volume sets until
241 failure (with/without blood flow restriction) 3) split squat with progressive loading in a
242 traditional periodization scheme until reaching the recommended prescription for maximal
243 strength 4) split squat performed accordingly with maximal strength recommendations, with
244 potential adaptations highlighted in Table 1.

245 INSERT TABLE 1.

246 ***2.3 Using isometric strength training to target deficits***

247 From a rehabilitation perspective, isometric contractions may be employed during
248 specific phases where dynamic contractions may be contraindicated. Although dependent on
249 the persistent musculoskeletal condition analysed, isometric contractions are capable of

250 inducing hypoalgesia for chronic hand, knee, and shoulder injuries [114], also during in-
251 season [115, 116]. The hypoalgesic effect is however, variable and not always consistent
252 [117, 118]. This may depend on the population analysed, the tissues properties, the physical
253 activity level, and the pain modulation profile of the subjects assessed [119-123].

254 During isometric contractions, the muscle-tendon unit remains at a constant length.
255 Isometric muscle actions have been widely used due to their tightly controlled application of
256 force at specific joint-angles, their ability to develop greater force than concentric
257 contractions, and their high reliability in assessing and tracking force production [124].
258 Isometric training at long muscle lengths and at high volumes are more effective for inducing
259 muscle hypertrophy than at short muscle lengths [125-127], potentially due to greater blood
260 flow occlusion, rates of oxygen consumption, and metabolite build-up [128]. Although it may
261 not be an effective strategy for directly improving sports performance, isometric training
262 shows the largest improvements at the trained angles [124]. This has connotations for athletes
263 who are rehabilitating following injury. For example, in ACL deficient subjects, angle
264 specific quadriceps muscle torque between-limb deficits were more evident at angles of less
265 than 40 degrees knee flexion as opposed to the peak torque recorded during the trial (not
266 considering the angle at which this occurred) [129, 130]. This may reveal the potential utility
267 of implementing positional isometrics in a rehabilitation programme for ACL deficient
268 patients. Similarly, isometric quadriceps muscle actions, using the leg extension machine at
269 80% of the MVIC, and holding for 45 seconds for 5 sets, with one minute between sets, may
270 be employed for subjects with patellar tendinopathy when isotonic contractions are not
271 tolerated or during in season [115, 116, 131].

272

273 **3.0 Rate of Force and Torque Development**

274 ***3.1 The importance of rate of force development***

275 Rate of Force Development (RFD) is defined as the ability of the neuromuscular
276 system to produce a high rate of rise in muscle force per unit of time during the initial phase
277 following contraction onset [45]; torque refers to a force that causes rotation. Contractile
278 RFD is a parameter used for measuring “explosive” strength capabilities. It is determined
279 from the slope of the force time curve (generally between 0 and 250 milliseconds), and
280 calculated as $\Delta\text{Force}/\Delta\text{Time}$. Several factors can impact RFD, particularly the early phase (<

281 100 ms relative to contraction onset), which is more influenced by intrinsic muscle properties
282 and neural drive, while the late phase (>100 ms relative to contraction onset) is more
283 respondent to maximal muscle strength [45, 132]. Considering that force application during
284 skills such as sprinting, jumping, throwing, and kicking last approximately 30–200
285 milliseconds [56], RFD is a critical performance characteristic central to success in most
286 power-based sporting events, as well as endurance running performance [133].

287 ***3.2 RFD deficits following injury***

288 In addition to the short time frames available to execute sporting tasks, it has been
289 demonstrated that non-contact ACL tears occur in a timeframe of less than 50 milliseconds,
290 while the quadriceps, for example, requires more than 300 milliseconds to reach peak torque
291 during isometric testing [22]. Angelozzi et al. [19] found significant deficits in RFD at six
292 months post-ACLR in professional soccer players who had completed a typical standardized
293 rehabilitation program and achieved nearly full recovery in the International Knee
294 Documentation Committee (IKDC), Tegner activity scale, KT1000 and MVIC, which are
295 objective measures commonly used to guide return to sports decision making. Similarly,
296 Kline et al. [22] demonstrated reduced quadriceps RFD in subjects at six months post ACLR
297 with patellar tendon autograft.

298 Deficits in RFD have also been shown in other common pathologies. For example,
299 Nunes et al. [18] found reduced RFD in hip abduction and extension in a cohort of physically
300 active females with patellofemoral pain. In addition, Wang et al. [20] demonstrated lower
301 values in early RFD in the triceps surae muscle in elite athletes with unilateral chronic
302 Achilles tendinopathy, while Opar et al. [23] showed lower rate of torque development in
303 previously injured hamstrings. Cumulatively, the available evidence indicates that restoration
304 of the ability to apply high forces in short time frames is crucial from both a rehabilitative
305 and performance perspective.

306 ***3.3 Using training to target RFD deficits***

307 The available evidence indicates that training at high velocities or with the intention to
308 move loads quickly, is highly effective in eliciting marked gains in rapid force production
309 capacity [132, 134-136]. This includes medicine ball throws, plyometrics [137], Olympic
310 weightlifting and their derivatives [55, 138] (see Table 2 for further examples). The
311 prescription of these can be best appreciated by defining the mechanical parameters that

312 underpin power. Mechanically, power is the work performed per unit of time, or force
313 multiplied by velocity. The inverse relationship between force and velocity can be illustrated
314 by the force-velocity (FV) curve (Figure 1), which identifies that maximum strength is
315 exerted under high loads, and maximum speed is produced under low loads [56].
316 Subsequently, the goal of strength and conditioning programming is to improve force
317 capability under the full spectrum of loads and thus velocities. For example, emerging
318 evidence shows how different force-velocity profiles exist within individuals; thus,
319 suggesting that improving maximal strength may be most beneficial for some athletes, while
320 others may benefit most from improving force at high velocity [138, 139]. This has been
321 shown recently by Jimenez-Reyes et al. [139] who tailored the training programme based on
322 the Force-Velocity profile during jumping. An individualized training programme
323 specifically based on the difference between the actual and optimal Force-Velocity profiles of
324 each individual (F-V imbalance) was more effective in improving jumping performance than
325 traditional resistance training common to all subjects (velocity-deficit, force-deficit, and well-
326 balanced increased by $12.7 \pm 5.7\%$ ES= 0.93 ± 0.09 , $14.2 \pm 7.3\%$ ES= 1.00 ± 0.17 , and $7.2 \pm$
327 4.5% ES= 0.70 ± 0.36 , respectively). Furthermore, despite being just a case report,
328 Mendiguchia et al. found that the capability to produce horizontal force at low speed (FH0)
329 was altered both before and after return to sport from a hamstring injury in two professional
330 athletes; thus, changing the slope of the F-V relationship [140]. The data collectively show
331 that athletes need a well-rounded approach that prepares them to tolerate high and low loads
332 as well as high and low velocities, not only from a performance perspective, but also to
333 empower resilience to different stress stimuli and to increase musculoskeletal robustness.

334 INSERT FIGURE 1.

335 INSERT TABLE 2.

336

337 **4.0 Reactive Strength**

338 ***4.1 The importance of reactive strength***

339 Eccentric actions are those in which the musculotendinous unit actively lengthens
340 throughout the muscle action. Eccentric training has received considerable attention due to its
341 potentially more favourable adaptations compared to concentric, isometric, and traditional
342 isotonic (eccentric/concentric) training [141, 142]. These include superior benefits for

343 isometric and concentric strength, preferential recruitment of type II muscle fibers, power,
344 RFD and stiffness, muscle architecture, and increased muscle activation, as well as improved
345 performance in sporting actions [44, 143, 144]. Forceful eccentric contractions may have a
346 superior impact in reducing intra-cortical inhibition and in increasing intra-cortical
347 facilitation [111, 145]. These improvements can occur where there are high eccentric stretch-
348 loads, such as landing and change of direction mechanics, and fast stretch-shortening cycle
349 (SSC) demands, because an athlete's reactive-strength ability is underpinned by relative
350 maximal eccentric strength [146]; this again reinforces the need of substantial high levels of
351 strength values before developing SSC capabilities [59]. The reactive strength index (RSI)
352 has been widely employed to quantify plyometric or SSC performance, that is the ability to
353 change quickly from an eccentric to concentric muscle action [147]. The factors that underpin
354 an efficient SSC are related to the storage and the reutilization of elastic energy. These are the
355 result of a number of mechanisms including utilization of intrinsic muscle-tendon stiffness,
356 involuntary reflex muscle activity, antagonistic co-contraction, and the SSC pre-stretch [148].
357 The latter, referred also as pre-activation during the eccentric phase, may allow for a greater
358 number of motor units to be recruited during the concentric contraction through neural
359 potentiation, thus indicating the important role of eccentric force production in SSC
360 capabilities [147, 149].

361 The RSI can be used to assess leg stiffness. This can be described as the resistance to
362 the deformation of the lower limb in response to an applied force. Therefore, a certain
363 amount of lower extremity stiffness is required for effective storage and re-utilization of
364 elastic energy in SSC activities [133]. Lower extremity stiffness is considered to be a key
365 attribute in the enhancement of running, jumping and hopping activities [150, 151]. Indeed,
366 numerous studies reported that lower extremity stiffness increases with running velocity and
367 this is concomitant with increased vertical ground reaction forces (GRFs), increased ground
368 contact frequency, and shorter ground contact times [149, 152]. SSC activities have been
369 divided into fast SSC (<250ms) and slow SSC (>250ms) accordingly with the ground contact
370 time.

371 ***4.2 Reactive strength deficits following injury***

372 Emerging evidence shows the importance of incorporating drop jumps in the
373 evaluation of RSI as criteria for return to play. King et al. [26] revealed that the single leg
374 drop jump identified greater performance deficits between the ACL reconstructed limb and

375 the non-operated limb compared to the single leg hop for distance, suggesting insufficient
376 rehabilitation status at nine months post-surgery. Incomplete restoration of reactive strength
377 and stiffness capabilities may also be present in the periods following a range of other
378 injuries. Gore et al. [27] found that hip abductor stiffness was impaired in a cohort of subjects
379 with athletic groin pain compared to controls and that this difference was no longer
380 significant after the rehabilitation period. In the presence of Achilles Tendinopathy, several
381 studies have shown that the tendon mechanical properties [153, 154], modulations of the
382 SSC, leg stiffness, and RFD are altered [20, 28, 29]. This is in contrast with the normal
383 function of the tendon complex, whose key role is to store, recoil and release energy while
384 maintaining optimal efficiency in power production [155].

385 ***4.3 Using training to target reactive strength deficits***

386 Attainment of an adequate strength level is fundamental to the development of reactive
387 strength as discussed previously. In addition, plyometric training can enhance early and late
388 RFD as well as optimizing leg stiffness and the modulation of the SSC [55, 156]. Plyometric
389 training exploits the rapid cyclical muscle action of the SSC whereby the muscle undergoes a
390 lengthening movement (“eccentric muscle action”), followed by a transitional period prior to
391 the shortening movement (“concentric contraction”) and can be used to improve eccentric
392 force generation capacity. Flanagan et al. [147] suggested a 4 step progression focusing on
393 the eccentric jumping action while landing (phase 1); rebound spring like actions with short
394 ground contact times (phase 2); hurdle jumps with an emphasis on short ground contact while
395 increasing intensity of the eccentric stimulus (phase 3); and finally depth jumps in order to
396 maximise jump height while maintaining minimal ground contact times (phase 4) (Table 3).
397 Furthermore, progressive training intensities might be an effective prescription to achieve
398 improvements in change of direction ability [150, 157].

399 Alternative strategies for athletes who have attained the requisite level of strength
400 include accentuated eccentric loading (AEL) to increase eccentric strength via supra-maximal
401 loading [141, 146]. Examples include adopting weight releasers or dumbbells dropped in the
402 bottom position in order to overload the eccentric portion of the movement, enhancing the
403 subsequent concentric action. Patients post ACLR who are a substantial time period from
404 their surgery and have reached normative strength values across different ranges of motion
405 and velocities, may benefit from AEL to further increase quadriceps eccentric strength [158],
406 together with progressive intensities of plyometric training. However, AEL by definition is

407 not commonly employed in rehabilitation strategies, although sports medicine professionals
408 are now widely applying eccentric loads for the prevention and rehabilitation of hamstring
409 injuries. The Nordic hamstring exercise has been shown to significantly reduce the risk of
410 hamstring injuries [159-161]. Furthermore, even a low training volume can stimulate
411 increases in fascicle length and improvements in eccentric knee flexor strength [162].
412 Similarly, the Copenhagen adduction exercise is commonly prescribed due to its superior
413 ability to increase eccentric hip adduction strength [82] and the eccentric triceps surae
414 exercise has been shown not only to increase maximal strength, tendon stiffness, Young's
415 modulus and tendon CSA [60, 107, 163], but also ankle dorsiflexion [164] and the SSC
416 behaviour.

417 Practically, AEL can be applied by completing the concentric portion of the movement with
418 both limbs at high loading schemes and by using only the involved limb for the eccentric
419 portion, thus resulting in load above 100% of 1RM. Similarly, the athlete may also be
420 assisted during the concentric portion of the exercise while the eccentric portion is completed
421 independently. Alternatively, the use of heavy chains allows increases of load during both the
422 early concentric phase of the lift as well as early eccentric phase of the descent, due to the
423 favourable muscle leverage and the additional chain links [165].

424 INSERT TABLE 3.

425

426 **5.0 Return to play tests and the need to test multiple physical capacities**

427 A recent review on the topic of ACL rehabilitation summarised that there is a high rate
428 of return to sport overall (81%-82%) but a lower rate for competitive sports (44%-55%).
429 These data appear to be dictated by fear of re-injury as well as functional capabilities of the
430 reconstructed knee; the latter tended to be deemed optimal when both Limb Symmetry Index
431 and hop tests reach at least 90% of the contralateral limb [16]. However, Arden et al. [166]
432 found that, despite obtaining what was considered normal strength values, the rate of return
433 to sport was low. This suggests that evaluating maximal strength at low velocities only, as per
434 current most common criteria to return athletes to unrestricted sports activities, is not
435 sufficient. Indeed, a recent review [167] analysed the discharge criteria for RTS following
436 primary ACLR in studies published from 2001 to 2011, revealing that 85% of studies used
437 time based measures as RTS criterion. Strength criteria were reported in 41% of studies,

438 whereas physical performance based criteria in only 20% of studies. This may indicate a
439 potential gap in the implementation of performance strategies and tests in rehabilitation
440 settings. Return to play criteria should therefore also consider multiple physical capacities
441 and assessments of maximal strength, reactive strength, RFD and power capabilities along
442 the whole F-V curve and in multiple planes, in addition to vertical jumps, change of
443 directions, acceleration, deceleration and speed actions as dictated by each individual's sports
444 demands through the completion of a comprehensive needs analysis.

445

446 **6.0 Program Design**

447 When attempting to maximize power output, provided that a high overall level of
448 strength has been reached, a periodized mixed methods approach, in which a variety of loads
449 and exercise types are used is suggested. This is because it allows a more complete
450 development of the force-velocity relationship (figure 1) . The use of low-load, high-velocity
451 movements (such as unloaded jump squats) may have a greater influence on the high-velocity
452 area of the force-velocity curve, while heavier loads (e.g. used in the back squat) improve to a
453 greater degree the high-force portion [50]. Training modalities may therefore include
454 weightlifting exercises and/or derivatives, unilateral and/or bilateral training with a range of
455 loads, and plyometric or ballistic exercises in an appropriately periodized manner [55, 132,
456 168]. Optimal levels of maximal strength are the foundation for the development of efficient
457 SSC properties, as well as for ballistic sport-specific movements. Furthermore, volume and
458 intensity will be manipulated to maximise physical capabilities throughout their rehabilitation
459 as dictated by their ability to load safely in the context of their injury and also as the athlete
460 transitions towards a return to sports performance [169, 170]. Examples of potential
461 rehabilitation programmes are outlined in Table 4 and 5.

462 INSERT TABLE 4 AND 5.

463

464 **7.0 Conclusion**

465 This article has examined persistent deficits in fundamental physical qualities, such as
466 strength, rate of force development and reactive strength following injury. Training strategies
467 to target these deficits have also been discussed in order to increase an athlete's readiness to

468 return to sport. The concepts expressed in this article may help clinicians to reduce the gap
469 between rehabilitation and sports performance, while providing a means of tertiary
470 prevention following injury. Rehabilitation should not only aim to return athletes to play, but
471 also to full or enhanced performance. In order to achieve this, a strong cooperation among
472 health professionals, coaches and strength and conditioning specialists is essential.
473 Furthermore, implementation of the best available evidence of strength and conditioning and
474 exercise physiology is required to maximize training adaptation.

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478

479

480 **References**

- 481 1. Drew, M.K., B.P. Raysmith, and P.C. Charlton, *Injuries impair the chance of successful*
482 *performance by sportspeople: a systematic review*. Br J Sports Med, 2017. **51**(16): p. 1209-
483 1214.
- 484 2. Hagglund, M., et al., *Injuries affect team performance negatively in professional football: an*
485 *11-year follow-up of the UEFA Champions League injury study*. Br J Sports Med, 2013. **47**(12):
486 p. 738-42.
- 487 3. Williams, S., et al., *Time loss injuries compromise team success in Elite Rugby Union: a 7-year*
488 *prospective study*. British Journal of Sports Medicine, 2016. **50**(11): p. 651.
- 489 4. Windt, J., et al., *Does player unavailability affect football teams' match physical outputs? A*
490 *two-season study of the UEFA champions league*. J Sci Med Sport, 2018. **21**(5): p. 525-532.
- 491 5. Esteve, E., et al., *Preseason Adductor Squeeze Strength in 303 Spanish Male Soccer Athletes:*
492 *A Cross-sectional Study*. Orthop J Sports Med, 2018. **6**(1): p. 2325967117747275.
- 493 6. Hägglund, M., M. Waldén, and J. Ekstrand, *Risk Factors for Lower Extremity Muscle Injury in*
494 *Professional Soccer: The UEFA Injury Study*. The American Journal of Sports Medicine, 2012.
495 **41**(2): p. 327-335.
- 496 7. Arnason, A., et al., *Risk factors for injuries in football*. Am J Sports Med, 2004. **32**(1 Suppl): p.
497 5s-16s.
- 498 8. Hagglund, M., M. Walden, and J. Ekstrand, *Previous injury as a risk factor for injury in elite*
499 *football: a prospective study over two consecutive seasons*. Br J Sports Med, 2006. **40**(9): p.
500 767-72.
- 501 9. Fulton, J., et al., *Injury risk is altered by previous injury: a systematic review of the literature*
502 *and presentation of causative neuromuscular factors*. Int J Sports Phys Ther, 2014. **9**(5): p.
503 583-95.
- 504 10. Toohey, L.A., et al., *Is subsequent lower limb injury associated with previous injury? A*
505 *systematic review and meta-analysis*. Br J Sports Med, 2017. **51**(23): p. 1670-1678.
- 506 11. Jacobsson, J. and T. Timpka, *Classification of Prevention in Sports Medicine and*
507 *Epidemiology*. Sports Med, 2015. **45**(11): p. 1483-7.

- 508 12. Bourne, M.N., et al., *An Evidence-Based Framework for Strengthening Exercises to Prevent*
509 *Hamstring Injury*. Sports Medicine, 2017.
- 510 13. Delahunt, E., H. Fitzpatrick, and C. Blake, *Pre-season adductor squeeze test and HAGOS*
511 *function sport and recreation subscale scores predict groin injury in Gaelic football players*.
512 Phys Ther Sport, 2017. **23**: p. 1-6.
- 513 14. O'Neill, S., P.J. Watson, and S. Barry, *A Delphi study of risk factors for Achilles tendinopathy -*
514 *opinions of world tendon experts*. Int J Sports Phys Ther, 2016. **11**(5): p. 684-697.
- 515 15. Neal, B.S. and S.D. Lack, *Risk factors for patellofemoral pain: a systematic review and meta-*
516 *analysis*. British Journal of Sports Medicine, 2019. ;**53**:270-281.
- 517 16. Anderson, M.J., et al., *A Systematic Summary of Systematic Reviews on the Topic of the*
518 *Anterior Cruciate Ligament*. Orthop J Sports Med, 2016. **4**(3): p. 2325967116634074.
- 519 17. Thorborg, K., et al., *Eccentric and Isometric Hip Adduction Strength in Male Soccer Players*
520 *With and Without Adductor-Related Groin Pain: An Assessor-Blinded Comparison*. Orthop J
521 Sports Med, 2014. **2**(2): p. 2325967114521778.
- 522 18. Nunes, G.S., C.J. Barton, and F.V. Serrao, *Hip rate of force development and strength are*
523 *impaired in females with patellofemoral pain without signs of altered gluteus medius and*
524 *maximus morphology*. J Sci Med Sport, 2017.
- 525 19. Angelozzi, M., et al., *Rate of force development as an adjunctive outcome measure for*
526 *return-to-sport decisions after anterior cruciate ligament reconstruction*. J Orthop Sports
527 Phys Ther, 2012. **42**(9): p. 772-80.
- 528 20. Wang, H.K., et al., *Evoked spinal reflexes and force development in elite athletes with middle-*
529 *portion Achilles tendinopathy*. J Orthop Sports Phys Ther, 2011. **41**(10): p. 785-94.
- 530 21. Cobian, D.G., et al., *Knee Extensor Rate of Torque Development Before and After*
531 *Arthroscopic Partial Meniscectomy, With Analysis of Neuromuscular Mechanisms*. J Orthop
532 Sports Phys Ther, 2017. **47**(12): p. 945-956.
- 533 22. Kline, P.W., et al., *Impaired Quadriceps Rate of Torque Development and Knee Mechanics*
534 *After Anterior Cruciate Ligament Reconstruction With Patellar Tendon Autograft*. Am J Sports
535 Med, 2015. **43**(10): p. 2553-8.
- 536 23. Opar, D.A., et al., *Rate of torque and electromyographic development during anticipated*
537 *eccentric contraction is lower in previously strained hamstrings*. Am J Sports Med, 2013.
538 **41**(1): p. 116-25.
- 539 24. Doherty, C., et al., *Coordination and symmetry patterns during the drop vertical jump, 6-*
540 *months after first-time lateral ankle sprain*. J Orthop Res, 2015. **33**(10): p. 1537-44.
- 541 25. Doherty, C., et al., *Recovery From a First-Time Lateral Ankle Sprain and the Predictors of*
542 *Chronic Ankle Instability: A Prospective Cohort Analysis*. Am J Sports Med, 2016. **44**(4): p.
543 995-1003.
- 544 26. King, E., et al., *Whole-body biomechanical differences between limbs exist 9 months after*
545 *ACL reconstruction across jump/landing tasks*. Scand J Med Sci Sports, 2018.
- 546 27. Gore, S.J. and A. Franklyn-Miller, *Is stiffness related to athletic groin pain?* Scand J Med Sci
547 Sports, 2018. **28**(6): p. 1681-1690.
- 548 28. Debenham, J.R., et al., *Achilles tendinopathy alters stretch shortening cycle behaviour during*
549 *a sub-maximal hopping task*. J Sci Med Sport, 2016. **19**(1): p. 69-73.
- 550 29. Maquirriain, J., *Leg stiffness changes in athletes with Achilles tendinopathy*. Int J Sports Med,
551 2012. **33**(7): p. 567-71.
- 552 30. Pruyt, E.C., et al., *Relationship between leg stiffness and lower body injuries in professional*
553 *Australian football*. Journal of Sports Sciences, 2012. **30**(1): p. 71-78.
- 554 31. Lorimer, A.V. and P.A. Hume, *Stiffness as a Risk Factor for Achilles Tendon Injury in Running*
555 *Athletes*. Sports Med, 2016. **46**(12): p. 1921-1938.
- 556 32. O'Malley, E., et al., *Countermovement Jump and Isokinetic Dynamometry as Measures of*
557 *Rehabilitation Status After Anterior Cruciate Ligament Reconstruction*. J Athl Train, 2018.
558 **53**(7): p. 687-695.

- 559 33. Pratt, K.A. and S.M. Sigward, *Detection of Knee Power Deficits Following ACL Reconstruction*
560 *Using Wearable Sensors*. J Orthop Sports Phys Ther, 2018: p. 1-24.
- 561 34. Lee, D.W., et al., *Single-leg vertical jump test as a functional test after anterior cruciate*
562 *ligament reconstruction*. The Knee, 2018. **25**(6): p. 1016-1026.
- 563 35. Morin, J.B. and P. Samozino, *Interpreting Power-Force-Velocity Profiles for Individualized and*
564 *Specific Training*. Int J Sports Physiol Perform, 2016. **11**(2): p. 267-72.
- 565 36. Lorenz, D.S. and M.P. Reiman, *Performance enhancement in the terminal phases of*
566 *rehabilitation*. Sports health, 2011. **3**(5): p. 470-480.
- 567 37. Macdonald, B., et al., *The single-leg Roman chair hold is more effective than the Nordic*
568 *hamstring curl in improving hamstring strength-endurance in Gaelic footballers with previous*
569 *hamstring injury*. J Strength Cond Res, 2018.
- 570 38. Beyer, R., et al., *Heavy Slow Resistance Versus Eccentric Training as Treatment for Achilles*
571 *Tendinopathy: A Randomized Controlled Trial*. Am J Sports Med, 2015. **43**(7): p. 1704-11.
- 572 39. Lack, S., et al., *Proximal muscle rehabilitation is effective for patellofemoral pain: a*
573 *systematic review with meta-analysis*. Br J Sports Med, 2015. **49**(21): p. 1365-76.
- 574 40. Presland, J.D., et al., *The effect of Nordic hamstring exercise training volume on biceps*
575 *femoris long head architectural adaptation*. Scandinavian Journal of Medicine & Science in
576 Sports, 2018. **28**(7): p. 1775-1783.
- 577 41. Newton, R.U. and W.J. Kraemer, *Developing Explosive Muscular Power: Implications for a*
578 *Mixed Methods Training Strategy*. Strength & Conditioning Journal, 1994. **16**(5): p. 20-31.
- 579 42. Kawamori, N. and G.G. Haff, *The optimal training load for the development of muscular*
580 *power*. J Strength Cond Res, 2004. **18**(3): p. 675-84.
- 581 43. Cormie, P., M.R. McGuigan, and R.U. Newton, *Adaptations in athletic performance after*
582 *ballistic power versus strength training*. Med Sci Sports Exerc, 2010. **42**(8): p. 1582-98.
- 583 44. Suchomel, T.J., et al., *The Importance of Muscular Strength: Training Considerations*. Sports
584 Medicine, 2018. 48: 765.
- 585 45. Rodríguez-Rosell, D., et al., *Physiological and methodological aspects of rate of force*
586 *development assessment in human skeletal muscle*. Clin Physiol Funct Imaging, 2018. **38**(5):
587 p. 743-762.
- 588 46. Cormie, P., M.R. McGuigan, and R.U. Newton, *Developing maximal neuromuscular power:*
589 *Part 1--biological basis of maximal power production*. Sports Med, 2011. **41**(1): p. 17-38.
- 590 47. Hornsby, W.G., et al., *What is the Impact of Muscle Hypertrophy on Strength and Sport*
591 *Performance?* Strength & Conditioning Journal, 2018. **40**(6): p. 99-111.
- 592 48. Taber, C.B., et al., *Exercise-Induced Myofibrillar Hypertrophy is a Contributory Cause of Gains*
593 *in Muscle Strength*. Sports Medicine, 2019. **49**(7): p. 993-997.
- 594 49. Hughes, D.C., S. Ellefsen, and K. Baar, *Adaptations to Endurance and Strength Training*. Cold
595 Spring Harb Perspect Med, 2017. **8**(6).
- 596 50. Haff, G.G. and M.H. Stone, *Methods of Developing Power With Special Reference to Football*
597 *Players*. Strength & Conditioning Journal, 2015. **37**(6): p. 2-16.
- 598 51. Henneman, E., G. Somjen, and D.O. Carpenter, *Excitability and inhibitability of motoneurons*
599 *of different sizes*. J Neurophysiol, 1965. **28**(3): p. 599-620.
- 600 52. Clark, B.C., et al., *The power of the mind: the cortex as a critical determinant of muscle*
601 *strength/weakness*. J Neurophysiol, 2014. **112**(12): p. 3219-26.
- 602 53. Stone, M.H., et al., *The importance of isometric maximum strength and peak rate-of-force*
603 *development in sprint cycling*. J Strength Cond Res, 2004. **18**(4): p. 878-84.
- 604 54. Aagaard, P., et al., *Increased rate of force development and neural drive of human skeletal*
605 *muscle following resistance training*. J Appl Physiol (1985), 2002. **93**(4): p. 1318-26.
- 606 55. Haff, G.G. and S. Nimphius, *Training Principles for Power*. Strength & Conditioning Journal,
607 2012. **34**(6): p. 2-12.
- 608 56. Taber, C., et al., *Roles of Maximal Strength and Rate of Force Development in Maximizing*
609 *Muscular Power*. Strength & Conditioning Journal, 2016. **38**(1): p. 71-78.

- 610 57. Crewther, B.T., et al., *Baseline strength can influence the ability of salivary free testosterone*
611 *to predict squat and sprinting performance.* J Strength Cond Res, 2012. **26**(1): p. 261-8.
- 612 58. Comfort, P. and C. Thomas, *Changes in Dynamic Strength Index in Response to Strength*
613 *Training.* Sports **2018**, 6, 176.
- 614 59. James, L.P., et al., *The impact of strength level on adaptations to combined weightlifting,*
615 *plyometric, and ballistic training.* Scand J Med Sci Sports, 2018. **28**(5): p. 1494-1505.
- 616 60. Bohm, S., F. Mersmann, and A. Arampatzis, *Human tendon adaptation in response to*
617 *mechanical loading: a systematic review and meta-analysis of exercise intervention studies*
618 *on healthy adults.* Sports Medicine - Open, 2015. **1**(1): p. 7.
- 619 61. Kidgell, D.J., et al., *Corticospinal responses following strength training: a systematic review*
620 *and meta-analysis.* Eur J Neurosci, 2017. **46**(11): p. 2648-2661.
- 621 62. Watson, S.L., et al., *High-Intensity Resistance and Impact Training Improves Bone Mineral*
622 *Density and Physical Function in Postmenopausal Women With Osteopenia and*
623 *Osteoporosis: The LIFTMOR Randomized Controlled Trial.* J Bone Miner Res, 2018. **33**(2): p.
624 211-220.
- 625 63. Magnusson, S.P. and M. Kjaer, *The impact of loading, unloading, ageing and injury on the*
626 *human tendon.* J Physiol. 2019 Mar;597(5):1283-1298
- 627 64. Goodman, C.A., T.A. Hornberger, and A.G. Robling, *Bone and skeletal muscle: Key players in*
628 *mechanotransduction and potential overlapping mechanisms.* Bone, 2015. **80**: p. 24-36.
- 629 65. Grzelak, P., et al., *Hypertrophied cruciate ligament in high performance weightlifters*
630 *observed in magnetic resonance imaging.* International orthopaedics, 2012. **36**(8): p. 1715-
631 1719.
- 632 66. Ploutz, L., et al., *Effect of resistance training on muscle use during exercise.* Journal of
633 Applied Physiology, 1994. **76**: p. 1675–1681.
- 634 67. Stone, M., M. Stone, and W. Sands, *Principles and practice of resistance Training.* 2007, USA:
635 Human Kinetics.
- 636 68. Ploutz, L.L., et al., *Effect of resistance training on muscle use during exercise.* J Appl Physiol
637 (1985), 1994. **76**(4): p. 1675-81.
- 638 69. Baroni, B.M., et al., *Hamstring-to-Quadriceps Torque Ratios of Professional Male Soccer*
639 *Players: A Systematic Review.* J Strength Cond Res, 2018.
- 640 70. Grindem, H., et al., *Simple decision rules can reduce reinjury risk by 84% after ACL*
641 *reconstruction: the Delaware-Oslo ACL cohort study.* British journal of sports medicine, 2016.
642 **50**(13): p. 804-808.
- 643 71. Bourne, M.N., et al., *Eccentric Knee Flexor Strength and Risk of Hamstring Injuries in Rugby*
644 *Union: A Prospective Study.* Am J Sports Med, 2015. **43**(11): p. 2663-70.
- 645 72. Kyritsis, P., et al., *Likelihood of ACL graft rupture: not meeting six clinical discharge criteria*
646 *before return to sport is associated with a four times greater risk of rupture.* Br J Sports Med,
647 2016. **50**(15): p. 946-51.
- 648 73. Adams, D., et al., *Current concepts for anterior cruciate ligament reconstruction: a criterion-*
649 *based rehabilitation progression.* The Journal of orthopaedic and sports physical therapy,
650 2012. **42**(7): p. 601-614.
- 651 74. Ardern, C.L., et al., *2016 Consensus statement on return to sport from the First World*
652 *Congress in Sports Physical Therapy, Bern.* British Journal of Sports Medicine, 2016. **50**(14):
653 p. 853.
- 654 75. Grindem, H., et al., *How does a combined preoperative and postoperative rehabilitation*
655 *programme influence the outcome of ACL reconstruction 2 years after surgery? A*
656 *comparison between patients in the Delaware-Oslo ACL Cohort and the Norwegian National*
657 *Knee Ligament Registry.* British journal of sports medicine, 2015. **49**(6): p. 385-389.
- 658 76. Lauersen, J.B., D.M. Bertelsen, and L.B. Andersen, *The effectiveness of exercise interventions*
659 *to prevent sports injuries: a systematic review and meta-analysis of randomised controlled*
660 *trials.* British Journal of Sports Medicine, 2014. **48**(11): p. 871.

- 661 77. Malone, S., et al., *Can the workload-injury relationship be moderated by improved strength,*
662 *speed and repeated-sprint qualities?* J Sci Med Sport, 2019. **22**(1): p. 29-34.
- 663 78. Holden, S. and C.J. Barton, *'What should I prescribe?': time to improve reporting of*
664 *resistance training programmes to ensure accurate translation and implementation.* British
665 Journal of Sports Medicine, 2018. **53**:264-265.
- 666 79. Holden, S., et al., *How can we implement exercise therapy for patellofemoral pain if we don't*
667 *know what was prescribed? A systematic review.* Br J Sports Med, 2018. **52**(6): p. 385.
- 668 80. Murphy, M., et al., *Rate of Improvement of Pain and Function in Mid-Portion Achilles*
669 *Tendinopathy with Loading Protocols: A Systematic Review and Longitudinal Meta-Analysis.*
670 Sports Med, 2018. **48**(8): p. 1875-1891.
- 671 81. Malliaras, P., et al., *Achilles and patellar tendinopathy loading programmes : a systematic*
672 *review comparing clinical outcomes and identifying potential mechanisms for effectiveness.*
673 Sports Med, 2013. **43**(4): p. 267-86.
- 674 82. Ishoi, L., et al., *Large eccentric strength increase using the Copenhagen Adduction exercise in*
675 *football: A randomized controlled trial.* Scand J Med Sci Sports, 2016. **26**(11): p. 1334-1342.
- 676 83. Yousefzadeh, A., et al., *The Effect of Therapeutic Exercise on Long-Standing Adductor-Related*
677 *Groin Pain in Athletes: Modified Holmich Protocol.* Rehabilitation Research and Practice,
678 2018. **2018**: p. 10.
- 679 84. Sonnery-Cottet, B. and A. Saithna, *Arthrogenic muscle inhibition after ACL reconstruction: a*
680 *scoping review of the efficacy of interventions.* 2019. **53**(5): p. 289-298.
- 681 85. Hopkins, J.T. and C.D. Ingersoll, *Arthrogenic Muscle Inhibition: A Limiting Factor in Joint*
682 *Rehabilitation.* Journal of Sport Rehabilitation, 2000. **9**(2): p. 135-159.
- 683 86. Rice, D.A. and P.J. McNair, *Quadriceps arthrogenic muscle inhibition: neural mechanisms and*
684 *treatment perspectives.* Semin Arthritis Rheum, 2010. **40**(3): p. 250-66.
- 685 87. Pietrosimone, B.G., et al., *Neural Excitability Alterations After Anterior Cruciate Ligament*
686 *Reconstruction.* J Athl Train, 2015. **50**(6): p. 665-74.
- 687 88. Roy, J.S., et al., *Beyond the Joint: The Role of Central Nervous System Reorganizations in*
688 *Chronic Musculoskeletal Disorders.* J Orthop Sports Phys Ther, 2017. **47**(11): p. 817-821.
- 689 89. Chang, W.J., et al., *Altered Primary Motor Cortex Structure, Organization, and Function in*
690 *Chronic Pain: A Systematic Review and Meta-Analysis.* J Pain, 2018. **19**(4): p. 341-359.
- 691 90. Te, M., et al., *Primary Motor Cortex Organization Is Altered in Persistent Patellofemoral Pain.*
692 Pain Med, 2017. **18**(11): p. 2224-2234.
- 693 91. Fyfe, J.J., et al., *The role of neuromuscular inhibition in hamstring strain injury recurrence.* J
694 Electromyogr Kinesiol, 2013. **23**(3): p. 523-30.
- 695 92. Brockett, C.L., D.L. Morgan, and U. Proske, *Predicting hamstring strain injury in elite athletes.*
696 Med Sci Sports Exerc, 2004. **36**(3): p. 379-87.
- 697 93. Roig, M., et al., *The effects of eccentric versus concentric resistance training on muscle*
698 *strength and mass in healthy adults: a systematic review with meta-analysis.* Br J Sports
699 Med, 2009. **43**(8): p. 556-68.
- 700 94. Silder, A., et al., *MR observations of long-term musculotendon remodeling following a*
701 *hamstring strain injury.* Skeletal Radiol, 2008. **37**(12): p. 1101-9.
- 702 95. Bourne, M.N., et al., *Eccentric knee flexor weakness in elite female footballers 1–10 years*
703 *following anterior cruciate ligament reconstruction.* Physical Therapy in Sport, 2019. **37**: p.
704 144-149.
- 705 96. Brughelli, M., et al., *Contralateral leg deficits in kinetic and kinematic variables during*
706 *running in Australian rules football players with previous hamstring injuries.* J Strength Cond
707 Res, 2010. **24**(9): p. 2539-44.
- 708 97. Lord, C., et al., *Greater loss of horizontal force after a repeated-sprint test in footballers with*
709 *a previous hamstring injury.* J Sci Med Sport, 2019. **22**(1): p. 16-21.

- 710 98. Charlton, P.C., et al., *Knee flexion not hip extension strength is persistently reduced following*
711 *hamstring strain injury in Australian Football athletes: Implications for Periodic Health*
712 *Examinations.* J Sci Med Sport, 2018. **21**(10): p. 999-1003.
- 713 99. Rathleff, M.S., et al., *Is hip strength a risk factor for patellofemoral pain? A systematic review*
714 *and meta-analysis.* Br J Sports Med, 2014. **48**(14): p. 1088.
- 715 100. Rio, E., et al., *Tendon neuroplastic training: changing the way we think about tendon*
716 *rehabilitation: a narrative review.* Br J Sports Med, 2016. **50**(4): p. 209-15.
- 717 101. O'Neill, S., S. Barry, and P. Watson, *Plantarflexor strength and endurance deficits associated*
718 *with mid-portion Achilles tendinopathy: The role of soleus.* Phys Ther Sport, 2019. **37**: p. 69-
719 76.
- 720 102. Thorborg, K., *Why hamstring eccentrics are hamstring essentials.* Br J Sports Med, 2012.
721 **46**(7): p. 463-5.
- 722 103. Lauersen, J.B., D.M. Bertelsen, and L.B. Andersen, *The effectiveness of exercise interventions*
723 *to prevent sports injuries: a systematic review and meta-analysis of randomised controlled*
724 *trials.* Br J Sports Med, 2014. **48**(11): p. 871-7.
- 725 104. Kristensen, J. and A. Franklyn-Miller, *Resistance training in musculoskeletal rehabilitation: a*
726 *systematic review.* British Journal of Sports Medicine, 2012. **46**(10): p. 719.
- 727 105. Booth, J., et al., *Exercise for chronic musculoskeletal pain: A biopsychosocial approach.*
728 *Musculoskeletal Care,* 2017. **15**(4): p. 413-421.
- 729 106. *American College of Sports Medicine position stand. Progression models in resistance*
730 *training for healthy adults.* Med Sci Sports Exerc, 2009. **41**(3): p. 687-708.
- 731 107. Mersmann, F., S. Bohm, and A. Arampatzis, *Imbalances in the Development of Muscle and*
732 *Tendon as Risk Factor for Tendinopathies in Youth Athletes: A Review of Current Evidence*
733 *and Concepts of Prevention.* Frontiers in physiology, 2017. **8**: p. 987-987.
- 734 108. Schoenfeld, B.J., et al., *Strength and Hypertrophy Adaptations Between Low- vs. High-Load*
735 *Resistance Training: A Systematic Review and Meta-analysis.* J Strength Cond Res, 2017.
736 **31**(12): p. 3508-3523.
- 737 109. Schoenfeld, B.J., J. Grgic, and J. Krieger, *How many times per week should a muscle be*
738 *trained to maximize muscle hypertrophy? A systematic review and meta-analysis of studies*
739 *examining the effects of resistance training frequency.* Journal of Sports Sciences, 2018: p. 1-
740 10.
- 741 110. Hughes, L., et al., *Blood flow restriction training in clinical musculoskeletal rehabilitation: a*
742 *systematic review and meta-analysis.* British Journal of Sports Medicine, 2017. **51**(13): p.
743 1003.
- 744 111. Kidgell, D.J., et al., *Increased cross-education of muscle strength and reduced corticospinal*
745 *inhibition following eccentric strength training.* Neuroscience, 2015. **300**: p. 566-75.
- 746 112. Cirer-Sastre, R., J.V. Beltrán-Garrido, and F. Corbi, *Contralateral Effects After Unilateral*
747 *Strength Training: A Meta-Analysis Comparing Training Loads.* Journal of sports science &
748 *medicine,* 2017. **16**(2): p. 180-186.
- 749 113. Vaegter, H.B., *Exercising non-painful muscles can induce hypoalgesia in individuals with*
750 *chronic pain.* Scand J Pain, 2017. **15**: p. 60-61.
- 751 114. Naugle, K.M., R.B. Fillingim, and J.L. Riley Iii, *A Meta-Analytic Review of the Hypoalgesic*
752 *Effects of Exercise.* The Journal of Pain, 2012. **13**(12): p. 1139-1150.
- 753 115. Rio, E., et al., *Isometric Contractions Are More Analgesic Than Isotonic Contractions for*
754 *Patellar Tendon Pain: An In-Season Randomized Clinical Trial.* Clin J Sport Med, 2017. **27**(3):
755 p. 253-259.
- 756 116. Rio, E., et al., *Isometric Exercise to Reduce Pain in Patellar Tendinopathy In-Season; Is It*
757 *Effective "on the Road?".* Clin J Sport Med, 2017.
- 758 117. O'Neill, S., et al., *Acute sensory and motor response to 45-s heavy isometric holds for the*
759 *plantar flexors in patients with Achilles tendinopathy.* Knee Surg Sports Traumatol Arthrosc,
760 2018. **27**(9): p. 2765-2773.

- 761 118. Riel, H. and B. Vicenzino, *The effect of isometric exercise on pain in individuals with plantar*
762 *fasciopathy: A randomized crossover trial.* Scand J Med Sci Sports, 2018. **28**(12): p. 2643-
763 2650.
- 764 119. Lemley, K.J., S.K. Hunter, and M.K. Bement, *Conditioned pain modulation predicts exercise-*
765 *induced hypoalgesia in healthy adults.* Med Sci Sports Exerc, 2015. **47**(1): p. 176-84.
- 766 120. Naugle, K.M., et al., *Physical activity behavior predicts endogenous pain modulation in older*
767 *adults.* Pain, 2017. **158**(3): p. 383-390.
- 768 121. Naugle, K.M., et al., *Isometric exercise as a test of pain modulation: effects of experimental*
769 *pain test, psychological variables, and sex.* Pain Med, 2014. **15**(4): p. 692-701.
- 770 122. Sluka, K.A., L. Frey-Law, and M. Hoeger Bement, *Exercise-induced pain and analgesia?*
771 *Underlying mechanisms and clinical translation.* Pain, 2018. **159 Suppl 1**: p. S91-s97.
- 772 123. Coombes, B.K. and K. Tucker, *Achilles and patellar tendinopathy display opposite changes in*
773 *elastic properties: A shear wave elastography study.* Scand J Med Sci Sports, 2018. **28**(3): p.
774 1201-1208.
- 775 124. Oranchuk, D.J., et al., *Isometric training and long-term adaptations; effects of muscle length,*
776 *intensity and intent: A systematic review.* Scandinavian Journal of Medicine & Science in
777 Sports. Scand J Med Sci Sports, 2019. **29**(4): p. 484-503.
- 778 125. Alegre, L.M., et al., *Effects of isometric training on the knee extensor moment-angle*
779 *relationship and vastus lateralis muscle architecture.* Eur J Appl Physiol, 2014. **114**(11): p.
780 2437-46.
- 781 126. Kubo, K., et al., *Effects of isometric training at different knee angles on the muscle-tendon*
782 *complex in vivo.* Scand J Med Sci Sports, 2006. **16**(3): p. 159-67.
- 783 127. Noorkoiv, M., K. Nosaka, and A.J. Blazevich, *Neuromuscular adaptations associated with*
784 *knee joint angle-specific force change.* Med Sci Sports Exerc, 2014. **46**(8): p. 1525-37.
- 785 128. de Ruyter, C.J., et al., *Knee angle-dependent oxygen consumption during isometric*
786 *contractions of the knee extensors determined with near-infrared spectroscopy.* J Appl
787 Physiol (1985), 2005. **99**(2): p. 579-86.
- 788 129. Huang, H., et al., *Isokinetic angle-specific moments and ratios characterizing hamstring and*
789 *quadriceps strength in anterior cruciate ligament deficient knees.* Sci Rep, 2017. **7**(1): p.
790 7269.
- 791 130. Eitzen, I., et al., *Anterior cruciate ligament-deficient potential copers and noncopers reveal*
792 *different isokinetic quadriceps strength profiles in the early stage after injury.* Am J Sports
793 Med, 2010. **38**(3): p. 586-93.
- 794 131. Rio, E., et al., *Isometric exercise induces analgesia and reduces inhibition in patellar*
795 *tendinopathy.* British Journal of Sports Medicine, 2015. **49**(19): p. 1277-83.
- 796 132. Maffiuletti, N.A., et al., *Rate of force development: physiological and methodological*
797 *considerations.* Eur J Appl Physiol, 2016. **116**(6): p. 1091-116.
- 798 133. Brazier, J., et al., *Lower Extremity Stiffness: Considerations for Testing, Performance*
799 *Enhancement, and Injury Risk.* J Strength Cond Res, 2019. **33**(4): p. 1156-1166.
- 800 134. Andersen, L.L., et al., *Early and late rate of force development: differential adaptive*
801 *responses to resistance training?* Scand J Med Sci Sports, 2010. **20**(1): p. e162-9.
- 802 135. Tillin, N.A., M.T. Pain, and J.P. Folland, *Short-term training for explosive strength causes*
803 *neural and mechanical adaptations.* Exp Physiol, 2012. **97**(5): p. 630-41.
- 804 136. Balshaw, T.G., et al., *Training-specific functional, neural, and hypertrophic adaptations to*
805 *explosive- vs. sustained-contraction strength training.* J Appl Physiol (1985), 2016. **120**(11): p.
806 1364-73.
- 807 137. Butler, R.J., H.P. Crowell, 3rd, and I.M. Davis, *Lower extremity stiffness: implications for*
808 *performance and injury.* Clin Biomech (Bristol, Avon), 2003. **18**(6): p. 511-7.
- 809 138. Suchomel, T.J., P. Comfort, and J.P. Lake, *Enhancing the Force-Velocity Profile of Athletes*
810 *Using Weightlifting Derivatives.* Strength & Conditioning Journal, 2017. **39**(1): p. 10-20.

- 811 139. Jiménez-Reyes, P., et al., *Effectiveness of an Individualized Training Based on Force-Velocity*
812 *Profiling during Jumping*. *Frontiers in Physiology*, 2016. **7**: p. 677.
- 813 140. Mendiguchia, J., et al., *Field monitoring of sprinting power-force-velocity profile before,*
814 *during and after hamstring injury: two case reports*. *J Sports Sci*, 2016. **34**(6): p. 535-41.
- 815 141. Aagaard, P., *Spinal and supraspinal control of motor function during maximal eccentric*
816 *muscle contraction: Effects of resistance training*. *Journal of Sport and Health Science*, 2018.
817 **7**(3): p. 282-293.
- 818 142. Nishikawa, K., *Eccentric contraction: unraveling mechanisms of force enhancement and*
819 *energy conservation*. *The Journal of Experimental Biology*, 2016. **219**(2): p. 189.
- 820 143. Wagle, J.P., et al., *Accentuated Eccentric Loading for Training and Performance: A Review*.
821 *Sports Med*, 2017. **47**(12): p. 2473-2495.
- 822 144. Harden, M., et al., *An Evaluation of Supramaximally Loaded Eccentric Leg Press Exercise*. *J*
823 *Strength Cond Res*, 2018. **32**(10): p. 2708-2714.
- 824 145. Tallent, J., et al., *Enhanced Corticospinal Excitability and Volitional Drive in Response to*
825 *Shortening and Lengthening Strength Training and Changes Following Detraining*. *Frontiers*
826 *in physiology*, 2017. **8**: p. 57-57.
- 827 146. Beattie, K., et al., *The Relationship Between Maximal Strength and Reactive Strength*. *Int J*
828 *Sports Physiol Perform*, 2017. **12**(4): p. 548-553.
- 829 147. Flanagan, E.P. and T.M. Comyns, *The Use of Contact Time and the Reactive Strength Index to*
830 *Optimize Fast Stretch-Shortening Cycle Training*. *Strength & Conditioning Journal*, 2008.
831 **30**(5): p. 32-38.
- 832 148. Pedley, J.S., et al., *Drop Jump: A Technical Model for Scientific Application*. *Strength &*
833 *Conditioning Journal*, 2017. **39**(5): p. 36-44.
- 834 149. McBride, J.M., G.O. McCaulley, and P. Cormie, *Influence of preactivity and eccentric muscle*
835 *activity on concentric performance during vertical jumping*. *J Strength Cond Res*, 2008. **22**(3):
836 p. 750-7.
- 837 150. Asadi, A., et al., *The Effects of Plyometric Training on Change-of-Direction Ability: A Meta-*
838 *Analysis*. *Int J Sports Physiol Perform*, 2016. **11**(5): p. 563-73.
- 839 151. Lum, D., et al., *Effects of intermittent sprint and plyometric training on endurance running*
840 *performance*. *Journal of Sport and Health Science*, 2019. **8**(5): p. 471-477.
- 841 152. Butler, R.J., H.P. Crowell Iii, and I.M. Davis, *Lower extremity stiffness: Implications for*
842 *performance and injury*. *Clinical Biomechanics*, 2003. **18**(6): p. 511-517.
- 843 153. Child, S., et al., *Mechanical properties of the achilles tendon aponeurosis are altered in*
844 *athletes with achilles tendinopathy*. *Am J Sports Med*, 2010. **38**(9): p. 1885-93.
- 845 154. Obst, S.J., et al., *Are the Mechanical or Material Properties of the Achilles and Patellar*
846 *Tendons Altered in Tendinopathy? A Systematic Review with Meta-analysis*. *Sports Med*,
847 2018. **48**(9): p. 2179-2198.
- 848 155. Turner, A.N. and I. Jeffreys, *The Stretch-Shortening Cycle: Proposed Mechanisms and*
849 *Methods for Enhancement*. *Strength & Conditioning Journal*, 2010. **32**(4): p. 87-99.
- 850 156. Maloney, S.J., et al., *Unilateral Stiffness Interventions Augment Vertical Stiffness And Change*
851 *Of Direction Speed*. *J Strength Cond Res*, 2019. **33**(2): p. 372-379.
- 852 157. Maloney, S.J., et al., *Do stiffness and asymmetries predict change of direction performance?* *J*
853 *Sports Sci*, 2017. **35**(6): p. 547-556.
- 854 158. Lepley, L.K. and R. Palmieri-Smith, *Effect of eccentric strengthening after anterior cruciate*
855 *ligament reconstruction on quadriceps strength*. *J Sport Rehabil*, 2013. **22**(2): p. 150-6.
- 856 159. van der Horst, N., et al., *The preventive effect of the nordic hamstring exercise on hamstring*
857 *injuries in amateur soccer players: a randomized controlled trial*. *Am J Sports Med*, 2015.
858 **43**(6): p. 1316-23.
- 859 160. Arnason, A., et al., *Prevention of hamstring strains in elite soccer: an intervention study*.
860 *Scand J Med Sci Sports*, 2008. **18**(1): p. 40-8.

- 861 161. Petersen, J., et al., *Preventive effect of eccentric training on acute hamstring injuries in men's*
862 *soccer: a cluster-randomized controlled trial*. Am J Sports Med, 2011. **39**(11): p. 2296-303.
- 863 162. Presland, J.D., et al., *The effect of Nordic hamstring exercise training volume on biceps*
864 *femoris long head architectural adaptation*. Scand J Med Sci Sports, 2018. **28**(7): p. 1775-
865 1783.
- 866 163. Geremia, J.M., et al., *Effects of high loading by eccentric triceps surae training on Achilles*
867 *tendon properties in humans*. Eur J Appl Physiol, 2018. **118**(8): p. 1725-1736.
- 868 164. Aune, A.A.G., et al., *Acute and chronic effects of foam rolling vs eccentric exercise on ROM*
869 *and force output of the plantar flexors*. J Sports Sci, 2018: p. 1-8.
- 870 165. Ghigiarelli, J.J., et al., *The effects of a 7-week heavy elastic band and weight chain program*
871 *on upper-body strength and upper-body power in a sample of division 1-AA football players*. J
872 Strength Cond Res, 2009. **23**(3): p. 756-64.
- 873 166. Ardern, C.L., et al., *Return to sport following anterior cruciate ligament reconstruction*
874 *surgery: a systematic review and meta-analysis of the state of play*. Br J Sports Med, 2011.
875 **45**(7): p. 596-606.
- 876 167. Burgi, C.R., et al., *Which criteria are used to clear patients to return to sport after primary*
877 *ACL reconstruction? A scoping review*. British Journal of Sports Medicine, 2019. **53**(18): p.
878 1154-1161.
- 879 168. Comfort, P., J.J. McMahon, and T.J. Suchomel, *Optimizing Squat Technique - Revisited*.
880 Strength & Conditioning Journal, 9000. **Publish Ahead of Print**.
- 881 169. Kiely, J., *Periodization Theory: Confronting an Inconvenient Truth*. Sports Med, 2018. **48**(4):
882 p. 753-764.
- 883 170. Cunanan, A.J., et al., *The General Adaptation Syndrome: A Foundation for the Concept of*
884 *Periodization*. Sports Med, 2018. **48**(4): p. 787-797.

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