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Special article

Preventing or promoting muscle injuries? Strength training as a risk factor in professional football

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ABSTRACT

The rate of muscle injuries in professional football has not decreased despite the implementation of preventive strategies. This is commonly attributed to the rise in the number of competitions per season and the rigorous demands of modern football. However, these factors seem insufficient to explain the absence of impact from preventive strategies. Adopting a Network Physiology perspective, we hypothesize that some strength programs focused on reinforcing the most susceptible musculoskeletal structures and increase the muscle mass might contribute to, rather than mitigate, injuries in some players.

The aim of this work is twofold: a) explaining why some currently applied strength training methods may promote sports injuries in some players, and b) suggest the use of intermuscular connectivity measures to test the risk of injury.

The stability of multilevel neuromuscular synergies operating at various timescales is a crucial factor for adapting to strength training workloads. This stability necessitates long-term adaptation and cannot be assured through rapid strength gains. When neuromuscular synergies become unstable, the vulnerability to injuries rises. Since performance tests offer limited insights into the stability of neuromuscular synergies, we suggest employing recently developed intermuscular connectivity measures for monitoring and tracking players' progress.

Introduction

Despite the implementation of prevention strategies, the rate of muscle injuries in professional football has not decreased.[1, 2] The prevalence in youth players is particularly alarming and represents a significant health challenge.[3] Although a relationship between the head coach's leadership style and injury rates has been suggested,[4] there is a lack of studies relating muscle injuries with training methodologies. This brief opinion paper aims to alert that strength training may promote sports injuries in some players, and suggest the use of intermuscular connectivity measures to test the risk of muscle injuries.

The increase of hamstring injuries during the last decades in elite clubs has been linked to the high number of competitions per season and the rigorous demands of modern football.[1,5] It is a fact that successful teams participate in national and international cups, and their players frequently compete with their national teams. The interaction among competitive stress, extensive travel, and other related factors can lead to fatigue, coordination deterioration, and an elevated risk of injury.[6-8] However, preventive strategies, including nutrition, physiotherapy, and other interventions, specifically designed to alleviate these effects, have been notably implemented in recent years.[9-11] Furthermore, while the interactions of physiological, biomechanical, and psychosocial sports injury risk factors have been discussed, albeit partially addressed,[8,12] the impact of physical conditioning and training methodologies on muscle injuries keeps relatively understudied.

Although training soccer methodologies have notably evolved in recent years toward viewing players/teams as complex adaptive systems, strength and conditioning methodologies still treat players as sophisticated machines.[13,14] It is common to separate preventive and performance training using summative and commutative suppositions such as: "strength training combined with skill training results in performing skills with more strength", "strength training before field

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training has a preventive effect", "game actions can be trained in the gym through localized and unspecific exercises.

In recent years, professional football clubs have widely adopted strength training programs as a crucial component of the daily routines for footballers with the primary aim of preventing injuries. They are often based on localized and repetitive exercises which are specific to the performance tests but non-specific with respect to football actions. The potential influence of such methodologies relying on series and repetitions of the same exercises on the development of muscle synergies remains underexplored.[15,16] Traditional, contrast models, ballistic, plyometric, and eccentric programs, known for their substantial strength gains measured through performance tests, are among the most common applied methods.[17] They are typically conducted in dedicated gym facilities using weights, elastic bands, Olympic bars, ropes, medicine balls, etc. and before the field training sessions. It is worth to distinguish these routines focused on strength training from the widely used warming-up FIFA 11+ injury prevention program.[9]

The strength training programs mentioned above often lack robust scientific evidence, as it is the case of eccentric programs,[18-20] or lack evidence-based practice.[21] Moreover, existing evidences are frequently based on probabilistic results obtained through experimental designs of group data means comparisons which are non-adequate for personalized recommendations.[22,23]

Driven by prevailing social beliefs and values associated with body image, strength training practices have gained popularity, in particular, among youngsters. Muscular bodies, aligning with contemporary aesthetics and representing the archetype of a fit person, are exhibited by football stars and linked implicitly to success. From a complex system perspective, players, teams and competitions are nested structures related through circular causality.[24,14] If the conditional profile of professional football players changes, the game style and the competition changes as well. In turn, the game style and the competition constraints further the players profile. In this way, a generalized strength-oriented practice may change also the football competition, keeping aside the players with difficulties of adaptation to strength training.

Relying on the theoretical principles of the Network Physiology of Exercise,[25,26] the potential adverse effects of overloading footballers with strength training programs will be explained, and monitoring methods based on connectivity measures will be proposed to evaluate and track players progress.

Network approach to injuries. The connectivity hypothesis

Football actions emerge from the intricate interaction between multilevel physiological networks (e.g., molecules, cells, organs, limbs) and the environment.[27] Most muscle injuries occur performing actions that have been repeated many times without harmful consequences. To elucidate the nonlinear transition from safe to injurious actions, Pol et al. (2019) have proposed the connectivity of microinjuries hypothesis.[28] According to it, microinjuries, produced by any muscle action of significant intensity, can accumulate and interconnect over time. In general, if the rate of workloads overcome the time of tissue reparation,[29] clusters of microinjuries may create a context for the sudden emergence of a macroinjury. This means that one more repetition of a safe action can produce, through a percolation mechanism, a nonlinear effect (e.g., muscle strain or rupture).[28] As there is no universal threshold-safe number of repetitions or workload values, determining how much workload is too much is a persistently unsolved problem.[30,31] Several interacting factors (e.g. sleep, nutrition, life style) may delay the tissue repair requirements and increase the susceptibility to injury.[32] In this scenario, the widespread GPS-based technologies to quantify and track players workload may have a poor preventive power.

Qualitative changes in training routines, undetected by the tech-based monitoring systems, can also increase the susceptibility to injuries: the replacement of coaches, changes in training methodologies, shifts in tactical strategies or playing positions (e.g. when competing with clubs and national teams), resuming training after a resting period (e.g., preseason). Such changes are often overlooked by injury prevention strategies. However, the consideration of such coordinative stress factors becomes crucial in developing more comprehensive and effective injury prevention approaches.

Performance tests are not informative enough about injury risks

The accumulation of microinjuries induce coordinative changes in motor actions, similar to those produced by fatigue.[28] The explanation can be found in the loss of connectivity among muscle fibers and the instability of neuromuscular interactions.[33,34] The impact of fatigue on the muscular connectivity has been tested through the study of intermuscular coordination during exercise.[35,36] The authors have evaluated how distinct muscle fiber types dynamically interact with each other and integrate as a network while performing strength exercises (e.g. push-ups, squats). Specifically, they have measured intermuscular cross-frequency interactions among distinct muscles by quantifying the spectral components of different frequency bands embedded in surface electromyogram (sEMG) time series. Specific links strength among embedded networks have identified characteristic network profiles.

Fig. 1 shows the progressive loss of connectivity of muscle networks during three consecutive maximal squat tests.[36] The number and strength of connections among the muscle fibers is poorer in the third exercise compared to the first. However, due to synergetic muscle networks reorganization participants are able to continue performing the test requirements. This means that performance tests are not informative enough about changes in muscle connectivity and may poorly predict injury risks. When muscle fibers of the exercising muscle network compensate the lack of function of their neighbors, they become more and more overloaded and prone to increase and connect microinjuries.[28] When the number and/or strength of muscle fiber links decreases, the network becomes unfunctional,[25] and the susceptibility of suffering muscle injuries may increase. The empirical results of Fig. 1 strongly point to connectivity measures, obtained from spectral analysis of EMG time series of muscle groups during exercise, as a promising internal workload measure for preventing muscle injuries.

The loss of functional connectivity with fatigue has been also related to sedentarism and injuries.[25] In fact, severe muscle injuries have been associated with a high risk of reinjury.[37] Fatigue and injuries share similar dynamic laws and can be interpreted as adaptive protective mechanisms enforcing time for recovery.[28] In a similar manner that a poor muscle connectivity may induce a nonlinear effect like task failure,[33] it may induce a macroinjury.[28]

As noticed in early times, faster and high gains of strength were rapidly lost with detraining. In contrast, moderate gains obtained over longer periods of time were better retained.[38] In general, individual fitness profiles, which stabilize over generations, tend to decline after a temporary cessation of exercise at a rate inversely proportional to the accumulated training time.[39,40] This means that poorly stabilized strength muscle synergies may increase the susceptibility to injuries and vice versa. In this way, the adaptive response to strength training is highly individual, and depends on previous exposure to strength training and genetic factors. In fact, a high heterogeneity has been found in the adaptive response to strength training in older adults identifying adverse responders.[41]

Time scales of the muscle network and long-term adaptations

Adaptation to exercise is a consequence of functionally integrated multilevel physiological networks interacting with external workloads. These multilevel and multi timescale co-adaptive physiological networks interact with each other through circular causality during exercise.[40] Each level, acting on different characteristic timescale, parametrize the muscle synergies. The faster evolving processes (e.g., enzymatic or protein signaling network activity, neural excitability etc.)

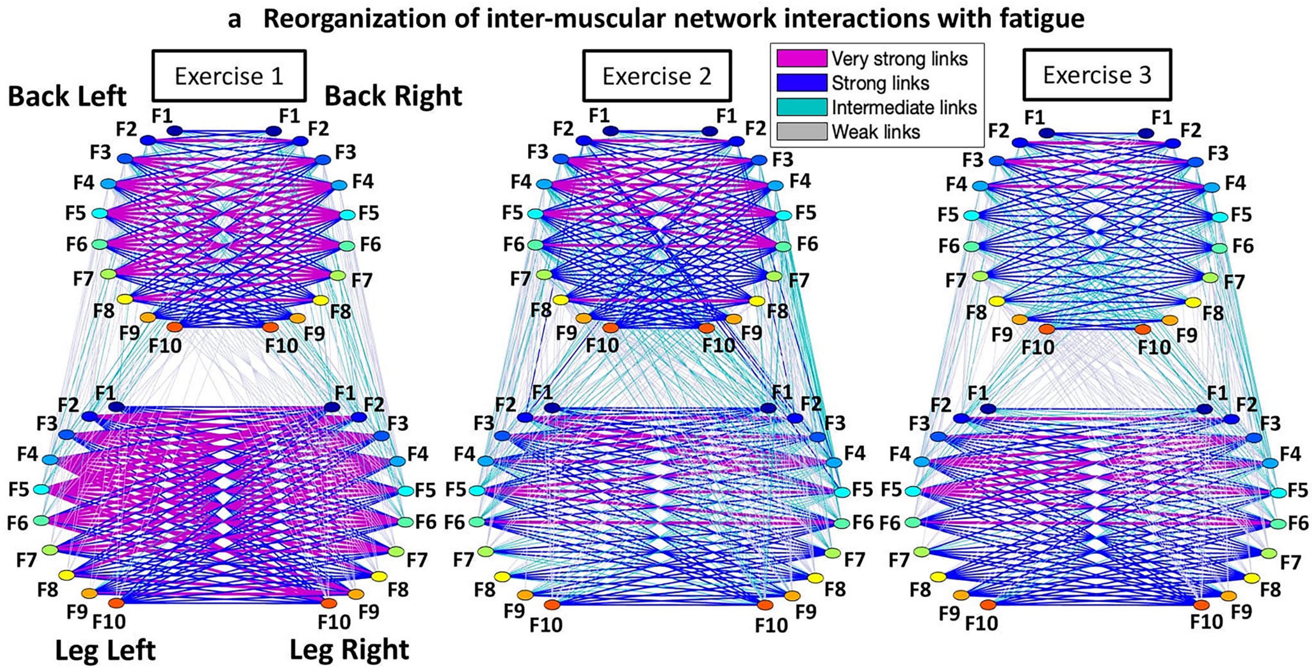

Fig. 1. Networks of interactions among muscle fibers of *erector espinae* (up) and *vastus lateralis* (down) during 3 consecutive bouts of squat exercises performed until exhaustion. The muscle network reorganizes with fatigue accumulation. The network maps represent the coupling strength between frequency bands (color nodes) corresponding to fast, intermediate and slow fibers within each muscle group. Links strength is shown by the width of the lines (adapted from García-Retortillo et al., 2022).[35]

may have already stabilized at increased values while the more slowly evolving variables (e.g., tendon and bone remodeling, muscle hypertrophy, capillarization, etc.) may not have stabilized yet. The resulting incoherence between these processes may eventually produce a poor stability of muscle synergies and may increase the susceptibility to injuries.[28]

Practical consequences to avoid injury risks

- Update the reductionist assumptions of physical conditioning by considering players as complex adaptive systems also at physiological level.
- Avoid the fragmentation of prevention and performance training.
- Evaluate the individual characteristics of players before imposing strength training programs.
- Eschew strength training programs before field training sessions to protect susceptible players.
- Promote moderate and long-term adaptations to strength training.
- Avoid the homogenization of players pushing a common conditional profile based on strength.
- Pay attention to changes in coordinative requirements not reflected in the common tracking control of workloads.
- Introduce connectivity measurements (e.g. intermuscular connectivity) to test the injury risks.

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Conflicts of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. Ekstrand J, Bengtsson H, Waldén M, Davison M, Khan KM, Hägglund M. Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: the UEFA Elite Club Injury Study from 2001/02 to 2021/22. *Br J Sports Med*. 2022;57(5):292–298. https://doi.org/10.1136/bjsports-2021-105407. Available from.
2. Hallén A, Tomás R, Ekstrand J, Bengtsson H, Van den Steen E, Hägglund M, et al. UEFA Women's Elite Club Injury Study: a prospective study on 1527 injuries over four consecutive seasons 2018/2019 to 2021/2022 reveals thigh muscle injuries to be most common and ACL injuries most burdensome. *Br J Sports Med*. 2024;58(3):128–135. https://doi.org/10.1136/bjsports-2023-107133. Available from.
3. Pfirrman D, Herbst M, Ingelfinger P, Simon P, Botzenhardt S. Analysis of Injury Incidences in Male Professional Adult and Elite Youth Soccer Players: a Systematic Review. *J Athl Train*. 2016;51(5):410–424. https://doi.org/10.4085/1062-6050-51.6.03. Available from.
4. Ekstrand J, Lundqvist D, Largerbäck L, Vouillamoz M, Papadimitiou N, Karlsson J. Is there a correlation between coaches' leadership styles and injuries in elite football teams? A study of 36 elite teams in 17 countries. *Br J Sports Med*. 2018;52(8):527–531. https://doi.org/10.1136/bjsports-2017-098001. Available from.
5. Bradley PS. Setting the Benchmark' Part 1: the Contextualised Physical Demands of Positional Roles in the FIFA World Cup Qatar 2022. *Biol Sport [Internet]*. 2024;41(1):261–270. https://doi.org/10.5114/biolsport.2024.131090. Available from.
6. Ekstrand J, Waldén M, Hägglund M. A congested football calendar and the wellbeing of players: correlation between match exposure of European footballers before the World Cup 2002 and their injuries and performers during that World Cup. *Br J Sports Med*. 2004;38(4):493–497. https://doi.org/10.1136/bjsm.2003.009134. Available from.
7. Meuwisse WH, Tyreman H, Hagel B, Emery C. A dynamic model of etiology in sport injury: the recursive nature of risk and causation. *Clin J Sport Med*. 2007;17(3):215–219. https://doi.org/10.1097/JSM.0b013e3180592a48. Available from.
8. Bittencourt NFN, Meuwisse H, De Michelis Mendonça L, Nettel Aguirre A, Ocarino JM, Fonseca ST. Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition—Narrative review and new concept. *Br J Sports Med [Internet]*. 2016;50(21):1309–1314. https://doi.org/10.1136/bjsports-2015-095850. Available from.
9. Sadigursky D, Braid JA, De Lira DNL, Machado BAB, Carneiro RJF, Colavolpe PO. The FIFA 11+ injury prevention program for soccer players: a systematic review.

BMC Sports Sci Med Rehabil. 2017;9:18. https://doi.org/10.1186/s13102-017-0083-z [Internet]Available from.
10. Stephenson SD, Kocan JW, Vinod AV, Kluczynski M, Bisson LJ. A comprehensive summary of systematic reviews on sports injury prevention strategies. *Orthop J Sports Med*. 2021;9(10), 23259671211035776. https://doi.org/10.1177/23259671211035776. Available from.
11. Rodas G, Gonzalez JR. Sportomics: futbol Club Barcelona's approach to personalized injury prevention. *Apunts Sports Med*. 2024;59(222). https://doi.org/10.1016/j.apunsm.2024.100445. Available from.
12. Bolling C, Van Mechelen W, Pasman HR, Verhagen E. Context matters: revisiting the first step of the 'sequence of prevention' of sports injuries. *Sports Med*. 2018;48(10): 2227–2234. https://doi.org/10.1007/s40279-018-0953-x. Available from.
13. Renshaw I, Davids K, Newcombe D, Roberts W. *The Constraints-Led approach: Principles For Sports Coaching and Practice Design*. London: Routledge; 2019.
14. Pol R, Balagué N, Ric A, Torrents C, Kiely J, Hristovski R. Training or synergizing? Complex systems principles change the understanding of sport processes. *Sports Med Open*. 2020;6(1):28. https://doi.org/10.1186/s40798-020-00256-9. Available from.
15. Ammar A, Boujelbance MA, Simak ML, Fuente EF, Rizzi N, Washif JA, et al. Unveiling the acute neurophysiological responses to strength training: an exploratory study on novices performing weightlifting bouts with different motor learning models. *Biol Sport*. 2024;41(2):249–274. https://doi.org/10.5114/biolsport.2024.133481. Available from.
16. Cheung VCK, Cheung BMF, Zhang-Lea JH, Chan ZYS, Ha SCW, Chen CY, et al. Plasticity of muscle synergies through fractionation and merging during development and training of human runners. *Nat Commun*. 2020;11(1):4356. https://doi.org/10.1038/s41467-020-18210-4. Available from.
17. Raya González J, Sánchez Sánchez J. Strength training methods for improving actions in football. *Apunts Educ. Fís. Esports*. 2018;132:72–93. https://doi.org/10.5672/apunts.2014-0983.es.(2018/2).132.06. Available from.
18. Fanchini M, Steendahl IB, Impellizzeri FM, Pruna R, Dupont G, Coutts AJ, et al. Exercise-based strategies to prevent muscle injury in elite footballers: a systematic review and best evidence synthesis. *Sports Med*. 2020;50(9):1653–1666. https://doi.org/10.1007/s40279-020-01282-z. Available from.
19. McCall A, Carling C, Davison M, Nedelec M, Le Gall F, Berthoin S, et al. Injury risk factors, screening tests and preventative strategies: a systematic review of the evidence that underpins the perceptions and practices of 44 football (soccer) teams from various premier leagues. *Br J Sports Med [Internet]*. 2015;49(9):583–589. https://doi.org/10.1136/bjsports-2014-094104. Available from.
20. McCall A, Dupont G, Ekstrand J. Injury prevention strategies, coach compliance and player adherence of 33 of the UEFA Elite Club Injury Study teams: a survey of teams' head medical officers. *Br J Sports Med*. 2016;50(12):725–730. https://doi.org/10.1136/bjsports-2015-095259. Available from.
21. Turner AN. What is evidence-based practice in strength and conditioning? *Strength Cond J*. 2024. https://doi.org/10.1519/SSC.0000000000000840.
22. Amrhein V, Greenland S, McShane B. Scientists rise up against statistical significance. *Nature*. 2019;567(7748):305–307. https://doi.org/10.1038/d41586-019-00857-9. Available fromAvailable from.
23. Almarcha M, Sturmberg J, Balagué N. Personalizing the guidelines of exercise prescription for health: guiding users from dependency to self-efficacy. *Apunts Sports Med*. 2024;59(223). https://doi.org/10.1016/j.apunsm.2024.100449. Available from.
24. Balagué N, Pol R, Torrents C, Ric A, Hristovski R. On the relatedness and nestedness of constraints. *Sports Med Open*. 2019;5(1):6. https://doi.org/10.1186/s40798-019-0178-z. Available from.
25. Balagué N, Hristovski R, Almarcha M, Garcia Retortillo S, Ivanov PC. Network Physiology of exercise: vision and perspectives. *Front Physiol*. 2020;11, 611550. https://doi.org/10.3389/fphys.2020.611550. Available from.
26. Ivanov PC. The new field of network physiology: building the human physiolome. *Front Netw Physiol*. 2021;1, 711778. https://doi.org/10.3389/fnetp.2021.711778. Available from.
27. Balagué N, Torrents C, Hristovski R, Kelso JAS. Sport science integration: an evolutionary synthesis. *Eur J Sport Sci*. 2017;17(1):51–62. https://doi.org/10.1080/17461391.2016.1198422. Available from.
28. Pol R, Hristovski R, Medina D, Balagué N. From microscopic to macroscopic sport injuries.Applying the complex dynamic systems approach to sports medicine: a narrative review. *Br J Sports Med*. 2019;53(19):1214–1220. https://doi.org/10.1136/bjsports-2016-097395. Available from.
29. Lavallee ME, Balam T. An overview of strength training injuries: acute and chronic. *Curr Sports Med Rep*. 2010;9(5):307–313. https://doi.org/10.1249/jsr.0b013e3181f3ed6d. Available from.
30. Andrade R, Wik EH, Rebelo-Marques A, Blanch P, Whiteley R, Espregueira-Mendes J, et al. Is the acute: chronic workload ratio (ACWR) associated with risk of time-loss injury in professional team sports? A systematic review of methodology, variables and injury risk in practical situations. *Sports Med*. 2020;50(9):1613–1635. https://doi.org/10.1007/s40279-020-01308-6. Available from.
31. Impellizzeri FM, Woodcock S, Coutts AJ, Fanchini M, McCall A, Vigotsky AD. What role do chronic workloads play in the acute to chronic workload ratio? Time to dismiss ACWR and its underlying theory. *Sports Med*. 2021;51(3):581–592. https://doi.org/10.1007/s40279-020-01378-6. Available from.
32. Doherty R, Madigan S, Warrington G, Ellis J. Sleep and nutrition interactions: implications for athletes. *Nutrients*. 2019;11(4):822. https://doi.org/10.3390/nu11040822. Available from.
33. Hristovski R, Balagué N. Fatigue-induced spontaneous termination point – Nonequilibrium phase transitions and critical behavior in quasi-isometric exertion. *Hum Mov Sci*. 2010;29(4):483–493. https://doi.org/10.1016/j.humov.2010.05.004 [Internet]Available from.
34. Vázquez P, Hristovski R, Balagué N. The path to exhaustion: time-variability properties of coordinative variables during continuous exercise. *Front Physiol*. 2016; 15(7):37. https://doi.org/10.3389/fphys.2016.00037. Available from.
35. Garcia-Retortillo S, Ivanov PC. Inter-muscular networks of synchronous muscle fiber activation. *Front Netw Physiol*. 2022;2, 1059793. https://doi.org/10.3389/fnetp.2022.1059793. Available from.
36. Garcia-Retortillo S, Romero-Gómez C, Ivanov PC. Network of muscle fibers activation facilitates inter-muscular coordination, adapts to fatigue and reflects muscle function. *Commun Biol*. 2023:6,891. https://doi.org/10.1038/s42003-023-05204-3 [Internet]Available from.
37. Ekstrand J, Hägglund M, Waldén M. Epidemiology of muscle injuries in professional football (soccer). *Am J Sports Med*. 2011;39(6):1226–1232. https://doi.org/10.1177/0363546510395879. Available from.
38. Hettinger T. *Isometrische Muskeltraining*. Stuttgard, Germany: Fischer-Verlag; 1966.
39. Zatsiorsky VM, Kraemer WJ, Fry AC. *Science and Practice of Strength Training*. Champaign: Human Kinetics; 2020.
40. Hristovski R, Balagué N, Stevanovski M. Long-term exercise adaptation. Physical aging phenomena in biological networks. *Front Netw Physiol*. 2023;3, 1243736. https://doi.org/10.3389/fnetp.2023.1243736. Available from.
41. deSantana DA, Castro A, Cavaglieri CR. Strength training volume to increase muscle mass responsiveness in older individuals: weekly sets based approach. *Front Physiol*. 2021;30(12), 759677. https://doi.org/10.3389/fphys.2021.759677. Available from.