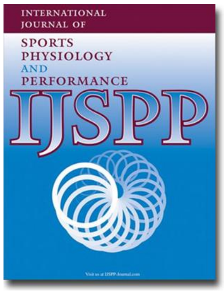

In press

Title: **Neuromuscular responses to conditioned soccer sessions assessed via GPS-embedded accelerometers: insights into tactical periodization**

Submission type: **Original investigation**

Authors: *M. Buchheit, M. Lacome, Y. Cholley, B.M. Simpson*

Performance Department, Paris Saint-Germain Football Club, Saint-Germain-en-Laye, France

Running Head: **Neuromuscular responses to conditioned soccer sessions**

Contact details:
Martin Buchheit
Performance Department, Paris Saint-Germain Football Club,
4a avenue du président Kennedy
78100 Saint-Germain-en-Laye, France
Tel.: +33 1 61 07 10 77
E-mail: mbuchheit@psg.fr

Abstract word count: **250**

Text-only word count: **3378**

Number of Tables: **3**

Number of Figures: **1**

Disclosures: nothing to disclose

1. Abstract

Purpose. To 1) examine the reliability of field-based running-specific measures of neuromuscular function assessed via GPS-embedded accelerometers and 2) examine their responses to three typical conditioned sessions (i.e., Strength, Endurance and Speed) in elite soccer players.

Methods. Before and immediately after each session, vertical jump (CMJ) and adductors squeeze strength (Groin) performances were recorded. Players also performed a 4-min run at 12 km/h followed by 4 ~60-m runs (run =12 s, r =33 s). GPS (15-Hz) and accelerometer (100 Hz) data collected during the four runs + the recovery periods excluding the last recovery period were used to derive vertical stiffness (K), peak loading force (peak force over all the foot-strikes, Fpeak) and propulsion efficiency (i.e., ratio between velocity and force loads, Vl/Fl).

Results. Typical errors were small (CMJ, Groin, K and Vl/Fl) and moderate (Fpeak), with moderate (Fpeak), high (K and Vl/Fl) and very high ICC (CMJ and Groin). After all sessions, there were small decreases in Groin and increases in K, while changes in F were all unclear. In contrast, the CMJ and Vl/Fl ratio responses were session-dependent: small increase in CMJ after Speed and Endurance, but unclear changes after Strength; the Vl/Fl ratio increased largely after Strength, while there was a small and a moderate decrease after the Endurance and Speed, respectively.

Conclusions. Running-specific measures of neuromuscular function assessed in the field via GPS-embedded accelerometers show acceptable levels of reliability. While the three sessions examined may be associated with limited neuromuscular fatigue, changes in neuromuscular performance and propulsion-efficiency are likely session objective-dependent.

Keywords: specificity; running mechanisms; fatigue; horizontal force application; association football.

2. Introduction

Within the tactical periodization training approach, tactical, technical, physiological and psychological elements are rarely trained in isolation, which is believed to improve specific motor skill acquisition and accelerate tactical learning.[1] In fact, daily training components are not only structured in relation to technical/tactical objectives, but also to the physical capacities to be targeted ("Physiological dimensions provide the biological framework where the soccer-specific training/recovery continuum lies"[1]). In practice, when playing once a week, the three principal training 'acquisition' days allow the successive development/maintenance of the main three physical capacities, i.e., strength, endurance and speed. Focusing deeper on a given quality on a given day likely allows the training stimulus to be maximized when the other qualities recover, which may decrease physiological interferences[2] and, in turn, lead to greater adaptations.[3] This so-called horizontal alternation in the physical components to be prioritized is often achieved while targeting all within-session training sequences towards the same quality. For example, a 'strength-conditioned session' would include a strength-oriented warm-up (e.g., light plyometric drills, single-leg horizontal hops), locomotor-based strength work (e.g., accelerations, changes of direction, sled pulling) and game-play sequences including, irrespective of the actual technical/tactical requirements, high and qualitative neuromuscular demands (e.g., high number of player/playing area ratio, maximal intensity of actions with adequate rest periods).

Despite the increasing interest for such a training approach, and despite the seducing theoretical basis of horizontal alternation, little is known about the actual loading and neuromuscular impact of these conditioned sessions. Quantifying the acute metabolic, running and musculoskeletal demands of these types of sessions, and more importantly assessing the level of lower limb-induced fatigue has important implications for optimal programming. To assess the neuromuscular responses and lower limb-induced fatigue following run-based team-sports sessions, various methods have been used, including non-running-specific (maximal voluntary contraction,[4] counter movement jump[5], hopping to calculate leg stiffness[4, 6]) or running-specific measures (maximal sprints, often sprint performance but more recently also the force/velocity profile of the sprints[7]). Since a great majority of force applications occur horizontally in run-based sports as soccer, and since neuromuscular fatigue is generally task-dependent,[8] non-running-specific measures may not be sensitive enough to capture the actual amount of fatigue induced by training sessions or games.[7] In contrast, running-specific measures of neuromuscular status, which are generally limited to (repeated) maximal sprints efforts,[7] are difficult to implement in an elite setting, and more importantly, can't be used regularly (injury risk, too demanding when playing schedules are tight). In order to overcome these latter limitations, we have recently developed a novel running-specific monitoring approach, which allows the measurement of stride variables in the field, using GPS-embedded accelerometers.[9] As such, run-based vertical stiffness, which has been shown to be affected by lower-leg muscle fatigue,[10, 11] can be tracked during any type of runs; maximal efforts are therefore no longer required, which makes data collection easier to implement in any context or population. Nevertheless, while good reliability of this monitoring approach has been shown under a controlled laboratory setting (i.e., small typical error of 6% for K on a treadmill[9]), the level of reliability of these variables in the field in real-life conditions with elite athletes has received little attention.[12] Considering that their reliability is good enough to assess running-specific fatigue in the field, the responses of these strides variables to typical conditioned training sessions may improve our understanding on how to best program these sessions within the training week.

The aims of the present study were to 1) examine the reliability of field-based running-specific measures of neuromuscular function (vertical stiffness, impact force and propulsion efficiency) assessed via GPS-embedded accelerometers) and 2) examine their responses to three typical conditioned sessions (i.e., targeting strength, endurance and speed qualities) in elite soccer players.

Methods

Participants. Data were collected in 18 players (17 ± 2 yrs) representative of an elite French academy, competing in both the 1st and 4th French divisions. They participated on average in ~10 hours of soccer-specific training and competitive play per week (~5-6 conditioned sessions + 1 game per week), alongside almost daily core and lower-body prevention work (~30 min). These data arose as a condition of player monitoring in which player activities are routinely measured over the course of the competitive season;[13] therefore, ethics committee clearance was not required. The study conformed nevertheless to the recommendations of the Declaration of Helsinki.

Study overview. All data were collected in-season within two consecutive weeks on artificial turf (Tarkett prestige, Field turf, Nanterre, France) during typical conditioned sessions, i.e., Strength (9.5°C, 75% relative humidity), Endurance (11.5°C, 80%) and Speed (12.0°C, 80%), at least 3 days after players' latest match. The same weekly training pattern was replicated over the two weeks, with Strength (Tuesday) and Speed (Thursday) sessions monitored the first week, and Endurance (Wednesday) the second.

Neuromuscular performance assessment.

Generic testing. Before and after each session, vertical jump performance (counter movement jump height, CMJ, Optojump Next, Microgate, Bolzano, Italia) and adductor squeeze strength (Groin, hand held dynamometer, PowerTrack II Commander, JTECH Medical, Salt Lake City, Utah) were recorded in the locker room (best of three trials after a standardized warm-up including adductions on an adductor ring). Using CMJ height as the only measure of jump-related neuromuscular fatigue has some limitations that should not be overlooked, since neuromuscular fatigue may also manifest as an altered movement strategy rather than just a diminished CMJ output.[14] Therefore, some variables other than jump height such as mean power or peak velocity, as measured with force plates may/may not better reflect fatigue in the context of the present investigation.[14] Whether the monitoring of a greater number of jumping variables would lead to conclusions different than those reported in the present study remains to be investigated.

Field-based running-specific measures. On the pitch, players' running activity (10-Hz GPS sampling with accelerometer data to produce a 15-Hz sampling rate, SPI-Pro, GPSports, Canberra, Australia), heart rate (HR), and rate of perceived exertion (RPE, 0-10 scale[15]) were recorded for each session. Each conditioned session started and ended with a standardized exercise sequence (~7 min), aimed at assessing locomotor-related neuromuscular status: a 4-min run at 12 km/h followed by 4 ~60-m runs (ran in 12 s, speed reached: 22-24 km/h, interspersed with a 33-s walked period). GPS and accelerometer data collected during the four runs + the recovery periods excluding the last recovery were used (Athletic Data Innovations, ADI, Sydney, Australia) to derive average vertical stiffness (K), peak loading force (instantaneous peak force derived from the magnitude vector of the triaxial accelerometer imbedded into the GPS units and relating to player body mass over all the foot-strikes, Fpeak, N) and propulsion efficiency (i.e., the ratio between velocity and force loads, Vl/Fl). Velocity load is calculated using player body mass and the running velocity across the entire sequence and increases by the power of 2 as speed increases. Force load is also derived by also utilising player body mass and the magnitude vector of the tri-axial accelerometer imbedded into the GPS units, with specific reference to the data relating to all the steps measured during the running sequence used for analysis (cumulative variable). While recordings from the scapulae may have limitations to assess lower-limb movement patterns in comparison with data collected around the center of mass,[16] this may not be a major limitation when using the ADI analyzer as in the present study. In fact, via improved signal processing taking into account body position and orientation (gyroscope), the present kinematic variables have been shown to be both valid and reliable when compared with a instrumented treadmill.[9] Additionally, we ensured that the devices were fitted securely in the same GPS vests (provided by the manufacturer) for all sessions. Players were all very familiar with the exercise procedures, which were included in their regular monitoring routines.

Conditioned sessions

The three sessions examined were representative of three typical conditioned sessions (i.e., Strength, Endurance and Speed, Table 1) targeting each of the three main physical capacities. While it is clear that other coaches would choose different drills and exercises, we believed that the most important aspect for the present study design was the horizontal alternation of contents within the same typical training week, within the same team (with the same certified and highly experienced coach designing the three sessions). Note that the conditioned session with the highest level of neuromuscular demands (left column in Table 1) was referred to as a 'Strength' session for consistency with the football-specific terminology both in the field and literature.[1] From a pure physiological standpoint, it is clear that neither the intensity (except for the PowerSprint exercises, there is no additional load and the level of strength involved is likely far beyond players' maximal strength) nor the format (short rests between repetitions, high volume, metabolic load combined) of such a session would be deemed to be appropriate to develop maximal strength per se.

Statistical analyses. Data in the text, tables and figures are presented as means with standard deviations (SD) and 90% confidence limits/intervals (CL/CI). All data were first log-transformed to reduce bias arising from non-uniformity error. The reliability of each variable was assessed while calculating both the typical error of measurement (TE, absolute reliability), expressed as a coefficient of variation (CV, 90% CL)[17] and standardized (Cohen's approach), and the intraclass correlation coefficient (ICC, 90% CL, relative reliability)[18] with a specifically-designed spreadsheet.[19] Within-session changes in the different variables, as well as between-session differences in the changes were examined using standardized differences, based on Cohen's effect size principle. Probabilities were used to make a qualitative probabilistic mechanistic inference about the true changes/differences in the changes, which were assessed in comparison to the smallest worthwhile change (0.2 x session SDs). The scale was as follows: 25−75%, possible; 75−95%, likely; 95−99%, very likely; >99%, almost certain.[20] Threshold values for standardized differences and standardized typical error were >0.2 (small), >0.6 (moderate), >1.2 (large) and very large (>2).[20] The magnitude of the ICC was assessed using the following thresholds: >0.99, extremely high; 0.99-0.90, very high; 0.90-0.75, high; 0.75-0.50, moderate; 0.50-0.20, low; <0.20, very low (WG Hopkins, unpublished observations).

3. Results

Reliability. The reliability statistics are shown in Table 2. TEs were small (CMJ, Groin and Vl/Fl) and moderate (K and Fpeak), with moderate (K and F), high (Vl/Fl) and very high ICC (CMJ and Groin).

Running, heart rate and subjective load of conditioned sessions. Complete data sets (session demands + all pre and post sessions tests) were obtained in 10 players. The running demands of the three sessions are presented in Table 3. As designed, total distance and average running pace were very largely and almost certainly greater, and time spent >90% of maximal HR slightly greater for Endurance compared with the two other sessions. Distance at high speed and peak velocity were very largely and almost certainly greater for Speed.

Neuromuscular responses to conditioned sessions. Within-session standardized changes in the different variables are shown in Figure 1 (upper panel). There were possible-to-very likely small decreases in Groin (-12% 90% CL (-18;-5), -7% (-16;-2) and -7% (-14;-1) for Strength, Endurance and Speed, respectively) and increases in K (12% (7;20), 16% (5;27) and 7% (-1;16)) after all three sessions, while changes in Fpeak were unclear. In contrast, CMJ and Vl/Fl ratio responses were session-dependent: there was a small increase in CMJ after Speed (+6% (1;13), likely) and Endurance (+5% (-1:12) possibly), but unclear changes after Strength (-2% (-11;7)); the Vl/Fl ratio increased largely and almost certainly after Strength (10% (6;13)), while there were likely small and moderate decreases after the Endurance (-6% (-11;0)) and Speed (-5% (-8;-1)), respectively.

Between-session standardized differences in the changes of these variables are shown in Figure 1 (lower panel). Of interest, compared with Strength, the increase in CMJ was likely slightly greater for Endurance (5% (2;11)) and Speed (7% (-2;16)). The increase in Vl/Fl after Strength was very largely and almost certainly greater than after Endurance (17% (11;22)) and Speed (16% (8;24)).

4. Discussion

The main findings of the present study were the following: 1) the running-specific variables showed small and moderate TEs, 2) CMJ didn't change or even increased slightly, K increased slightly and Fpeak wasn't clearly affected – the only measure that could indicate lower-leg fatigue was the decreased groin squeeze performance; however, the impairment was small in magnitude and 3) the changes in the Vl/Fl ratio were session-dependent: it increased very largely after Strength, while there was a small and a moderate decrease after the Endurance and Speed, respectively.

Reliability. The small TEs and very high ICC observed in the present study for CMJ and Groin squeeze (Table 2) were comparable to previous findings in similar populations (i.e., CV 5% and ICC 0.9 for CMJ,[21] CV 5% and ICC 0.9 for Groin[22]). In contrast, the CVs were greater (i.e., small and moderate magnitudes) for some of the run-based, accelerometer-derived indices (CV 7-17%, Table 2). While the moderate 7% TE for the Vl/Fl ratio was comparable to the 6% previously reported in similar conditions in the field,[12] the present between-day TE for K (11%, rated as small) was slightly greater than the within-day TE previously reported when tested on an indoor treadmill (6%, small[9]). Despite the tightly standardized protocol and the likely stable ground hardness between testing days (artificial turf), these differences could be attributed to the fact that in a real-life scenario with elite athletes as in the present study (i.e., tested within the training week, without a rest day and limited exercise standardization before data collection), training-induced variations in players' neuromuscular status between the different testing days may have increased the TE. Comparisons with the literature for Fpeak is however impossible, since this is the first time that the reliability of this measure derived from an accelerometer is examined. To conclude, while the small-to-moderate TEs observed for some of the running-specific measures (K and Fpeak) could be seen as a limitation to detect small amounts of fatigue in the field in comparison to the slightly more reliable non-running-specific indices (CMJ and Groin), their greater 'functional sensitivity' to fatigue[7] may (at least partly) overcome this 'statistical limitation'. Further studies comparing the responses of all these indices to an exercise inducing a clearly established amount of fatigue via gold standard measures of peripheral and central activation may be required to properly compare their respective sensitivity. It is also worth noting that considering CV values is not enough to understand the usefulness of (locomotor) variables to monitor individual players' responses to training.[23] In fact, CV values need to be regarded in relation to the usual changes observed in the variable of interest (signal) and the smallest worthwhile change (SWC), so that signal and noise can be compared (with the greater the signal-to-noise ratio, the greater the variable sensitivity). In the present study, except for Groin for which the CV ≈ SWC, the CVs were all ~2-3 x greater than the SWCs (Table 2), suggesting that only moderate to large changes can be detected with single CMJ, K, Fpeak and Vl/Fl measurements.[23] The following section will nevertheless exemplify the interest of accelerometer-derived K, Fpeak and the Vl/Fl ratio to better understand neuromuscular responses to typical conditioned sessions.

Running, heart rate and perceived load of strength-, speed- and endurance-oriented conditioned sessions. The specific demands of each conditioned session (Table 3) are in line with the training prescription principles of tactical periodization, i.e., the emphasis on a given physical component in each different session. For instance, knowing that an optimal endurance session may need to include a relatively-high average running pace, large activity volumes (duration and distance covered), and a minimum of 10-15 min spent in the 'red zone' (>90% of HRmax),[24] it was not surprising to observe very-largely greater total distance and average running pace during that session compared with the two others, which was also associated with 16 min spent >90% of HRmax (Table 3). Conversely, the fact that distance at high speed and peak velocity were very largely greater for the speed session than the two others also confirms the appropriate orientation of that session. Finally, the time-motion responses of the strength-oriented session may not reflect the true demands of that session for two main reasons: i) GPS are unfortunately not accurate enough (yet) to track short and high-speed COD sprints as performed during the session[25] (hence, not accordingly reflected by the Mechanical work index), ii) the highly-demanding neuromuscular actions of weight pulling (i.e., PowerSprint machine[26]) are not appropriately accounted for when analyzing movement-based activity via GPS (i.e., players move slowly while pulling hard, which is interpreted as a low acceleration work). The training contents (inclusion of plyometric drills, CODs, strength stations and 4x4 game format over a small playing area) suggest however that the physical objectives were likely matched.

Neuromuscular responses to strength-, speed- and endurance-oriented conditioned sessions. The first finding of the present study is that in overall, the three conditioned sessions were all associated with a limited amount of lower-leg fatigue: CMJ didn't change or even increased slightly, K increased slightly and Fpeak wasn't clearly affected – the only measure that could indicate lower-leg fatigue was the decreased groin squeeze performance; however, the impairment was small in magnitude (Figure 1, upper panel). Given the novelty of the present running-specific indices, the elite standard of the players and the fact that present data were collected in the field, there is unfortunately no data to compare the present results against. Changes in hopping-related K following session- or game simulation-induced fatigue have been inconclusive, with either increase,[6] no change[27] or decreased[4, 6] values reported. Mixed CMJ responses to team-sports sessions or game simulations have also been reported: no changes[27, 28] or decreases.[5] These inconsistencies are likely due to differences in study population (age,[29] individual characteristics[6]), exercise characteristics or K assessment and calculation (field vs. lab, hopping vs. running, center of mass displacement vs. ground reaction forces[6]). In the present study, the increase in CMJ after Speed and Endurance is probably attributable to a combined warm-up and muscle potentiation effect,[30] which couldn't translate into an increased performance after Strength due to a possibly slightly greater degree of fatigue (the decrease in Groin being greater after Strength than the two others sessions, Figure 1 lower panel). The increase in K following the three session is also likely attributable to a potentiation effect.[6] The observation that K increased also following Strength in contrast to CMJ may be related to the fact that running-based vertical K is more likely ankle than hip/knee-related than CMJ. Finally, the lack of clear changes in Fpeak is consistent with previous results during repeated-sprints with football boots, where peak loading force was not affected even in the condition of a moderate fatigue (-3% in sprint performance, Cohen's d = -0.8), which also induced a very large decrease in K (-16%, d = -3).[11]

Another interesting finding is the differential change in the Vl/Fl ratio during the high-speed runs (22-24 km/h) following the strength- (large increase) vs. the speed- and endurance- sessions (moderate decreases, Figure 1). Of note, the magnitude of these changes were also the largest observed in the present study, and the Vl/Fl ratio increase following Strength was apparent in every player. The increase in this ratio, which can be interpreted as an improvement in propulsion efficiency (less force loads on the ground for a similar motion activity) could be explained by some sort of facilitation for muscle force application[31] consecutive to the strength exercises, especially those involving horizontally-oriented force production (e.g., weight pulling, resisted sprints). At first sight, it could be hypothesized that this apparent movement facilitation may result more from a better intramuscular coordination or adjusting stride mechanics than an actual muscle potentiation, if we consider that after Strength Groin decreased and that changes in CMJ were unclear. It could however also be argued that the actual level of anterior chain potentiation matters little when it comes to running at high speed, where the hamstring muscles play a major role.[32] The reason for the substantial decrease in the Vl/Fl ratio following the other sessions remains a bit more surprising given the increased CMJ and K (Figure 1). Nevertheless, fatigue-specific changes in horizontal force application capability resulting from large amounts of high-speed running (Speed: 408 m > 19.8 km/h, Table 3) or training volume and metabolic loads (Endurance)[7, 33] that could affect posterior chain function may be involved. In fact, in a recent study, the reduction in sprinting capacity of Rugby seven players following an intense session was largely correlated with the amount of supramaximal running distance during the session.[7] To conclude, present data illustrates once more the task-specificity of neuromuscular fatigue,[8] with anterior chain (inferred from CMJ height, which although not without limitation[14] was affected more after Strength), adductors (Groin, fatigued after all) and posterior chain (high-speed runs, potentiated after Strength, fatigued after Speed and Endurance) all responding specifically to each of the conditioned sessions.

5. Practical applications

These results show that the typical conditioned sessions examined were well tolerated by elite players, and that only movement-specific neuromuscular fatigue may occur (small adductor fatigue after all sessions, large decrease in posterior chain efficiency after Speed and Endurance). While the evaluation of neuromuscular performance recovery wasn't examined the next day, it is very likely that fatigue may have dissipated at the start of the following session, given the small magnitude of the acute changes. These data suggest that the horizontal alternation in programming examined here may be optimal to minimize fatigue accumulation throughout the week when in-season, but it could also be argued that greater loads may need to be applied to generate acute fatigue, which could potentially trigger greater adaptations. The decision to vary training load/focus and, in turn, modulate acute neuromuscular fatigue may also depend on seasonal phases.[3] For example in contrast to pre-season, coaches tend to generally keep neuromuscular fatigue as minimal as possible when in-season to minimize injury risk and prioritize the quality of soccer-specific drills, and, in turn, optimize tactical/technical acquisitions. The other important findings are the very large improvement in propulsion efficiency following the session including horizontally-oriented strength work, and the large decrease following speed- and metabolically-oriented sessions. This may have direct implications for the design of game warm-ups, where the amount of horizontally-oriented neuromuscular activation work and high-speed running may need to be balanced to allow an efficient player preparation (muscle temperature, readiness to perform) while still benefiting performance. The exact structure of such warm-ups and how the Vl/Fl ratio may be affected requires further research.

6. Conclusions

While using reliable, running-specific measures of lower-limb function obtained with GPS-embedded accelerometers to compare the acute neuromuscular responses of three conditioned sessions (strength-, endurance- and speed-oriented), we found lower-limb fatigue to be small in magnitude, although the muscle groups affected were likely session orientation-dependent. These data suggest that the typical horizontal alternation in the physical capacity to be prioritized within a tactical periodization paradigm may be optimal to minimize neuromuscular fatigue accumulation throughout the week when in-season. Present results also show that exercises involving horizontally-oriented force application have the potential to acutely improve propulsion efficiency, while large high-speed running and high metabolic demands might compromise it. This novel information can be used for training programming and the design of appropriate pre-competition warm-ups.

7. Acknowledgements

The authors thank Laurent Huart and Maxime Coulerot for facilitating data collection, without which the present study could not be complete.

8. References

1. Delgado-Bordonau, J.L. and A. Mendez-Villanueva, *The Tactical Periodization Model.*, in *Fitness in Soccer: The science and Practical Application*, M.E. Sum, Editor. 2014.
2. Fyfe, J.J., D.J. Bishop, and N.K. Stepto, Interference between concurrent resistance and endurance exercise: molecular bases and the role of individual training variables. *Sports Med*, 2014;44(6):743-62.
3. Buchheit, M. and P.B. Laursen, High-intensity interval training, solutions to the programming puzzle. Part II: anaerobic energy, neuromuscular load and practical applications. *Sports Med*, 2013;43(10):927-54.
4. Lehnert, M., et al., Muscular and neuromuscular control following soccer-specific exercise in male youth: Changes in injury risk mechanisms. *Scand J Med Sci Sports*, 2016:[Epub ahead of print] Jun 10.
5. Iacono, A.D., et al., Game-profile-based Training in Soccer: A New Field Approach. *J Strength Cond Res*, 2016:[Epub ahead of print] Dec 8.
6. Oliver, J.L., et al., Altered neuromuscular control of leg stiffness following soccer-specific exercise. *Eur J Appl Physiol*, 2014;114(11):2241-9.
7. Marrier, B., et al., Quantifying Neuromuscular Fatigue Induced by an Intense Training Session in Rugby Sevens. *Int J Sports Physiol Perform*, 2016:1-19.
8. Enoka, R.M. and D.G. Stuart, Neurobiology of muscle fatigue. *J Appl Physiol*, 1992;72(5):1631-48.
9. Buchheit, M., A. Gray, and J.B. Morin, Assessing Stride Variables and Vertical Stiffness with GPS-Embedded Accelerometers: Preliminary Insights for the Monitoring of Neuromuscular Fatigue on the Field. *J Sports Sci Med*, 2015;14(4):698-701.
10. Morin, J.B., et al., Spring-mass model characteristics during sprint running: correlation with performance and fatigue-induced changes. *Int J Sports Med*, 2006;27(2):158-65.
11. Girard, O., et al., Repeated sprinting on natural grass impairs vertical stiffness but does not alter plantar loading in soccer players. *Eur J Appl Physiol*, 2011;111(10):2547-55.
12. Buchheit, M., Y. Cholley, and P. Lambert, Psychometric and Physiological Responses to a Preseason Competitive Camp in the Heat With a 6-Hour Time Difference in Elite Soccer Players. *Int J Sports Physiol Perform*, 2016;11(2):176-81.
13. Winter, E.M. and R.J. Maughan, Requirements for ethics approvals. *J Sports Sci*, 2009;27(10):985.
14. Gathercole, R., et al., Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *Int J Sports Physiol Perform*, 2015;10(1):84-92.
15. Impellizzeri, F.M., et al., Use of RPE-based training load in soccer. *Med Sci Sports Exerc*, 2004;36(6):1042-7.
16. Barrett, S., et al., Within-Match PlayerLoad Patterns During a Simulated Soccer Match: Potential Implications for Unit Positioning and Fatigue Management. *Int J Sports Physiol Perform*, 2016;11(1):135-40.
17. Hopkins, W.G., Measures of reliability in sports medicine and science. *Sports Med*, 2000;30(1):1-15.
18. Weir, J.P., Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res*, 2005;19(1):231-40.
19. Hopkins, W.G., Analysis of reliability with a spreadsheet. *Sportscience*, 2012:http://www.sportsci.org/resource/stats/xrely.xls.
20. Hopkins, W.G., et al., Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*, 2009;41(1):3-13.

21. Buchheit, M. and A. Mendez-Villanueva, Reliability and stability of anthropometric and performance measures in highly-trained young soccer players: effect of age and maturation. *J Sports Sci*, 2013;31(12):1332-43.
22. Thorborg, K., et al., Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scand J Med Sci Sports*, 2010;20(3):493-501.
23. Haugen, T. and M. Buchheit, Sprint Running Performance Monitoring: Methodological and Practical Considerations. *Sports Med*, 2015.
24. Buchheit, M. and P.B. Laursen, High-intensity interval training, solutions to the programming puzzle: Part I: cardiopulmonary emphasis. *Sports Med*, 2013;43(5):313-338.
25. Buchheit, M., et al., Integrating different tracking systems in football: multiple camera semi-automatic system, local position measurement and GPS technologies. *J Sports Sci*, 2014;32(20)(20):1844-1857.
26. Buchheit, M. and B.M. Simpson, Player Tracking Technology: Half-Full or Half-Empty Glass? *Int J Sports Physiol Perform*, 2016:1-23.
27. Cone, J.R., et al., Effects of an individualized soccer match simulation on vertical stiffness and impedance. *J Strength Cond Res*, 2012;26(8):2027-36.
28. Mayer, N., et al. *Reproducibility of physiological, neuromuscular and perceptual responses to small-sided games in highly-trained young soccer players*. in *European College of Sport Science*. 2013. Barcelona, June, 26th-29th.
29. De Ste Croix, M., et al., Leg Stiffness In Female Soccer Players: Inter-Session Reliability And The Fatiguing Effects Of Soccer-Specific Exercise. *J Strength Cond Res*, 2016.
30. Seitz, L.B. and G.G. Haff, Factors Modulating Post-Activation Potentiation of Jump, Sprint, Throw, and Upper-Body Ballistic Performances: A Systematic Review with Meta-Analysis. *Sports Med*, 2016;46(2):231-40.
31. Morin, J.B., P. Edouard, and P. Samozino, Technical ability of force application as a determinant factor of sprint performance. *Med Sci Sports Exerc*, 2011;43(9):1680-8.
32. Morin, J.B., et al., Sprint Acceleration Mechanics: The Major Role of Hamstrings in Horizontal Force Production. *Front Physiol*, 2015;6:404.
33. Girard, O., A. Mendez-Villanueva, and D. Bishop, Repeated-sprint ability - part I: factors contributing to fatigue. *Sports Med*, 2011;41(8):673-94.

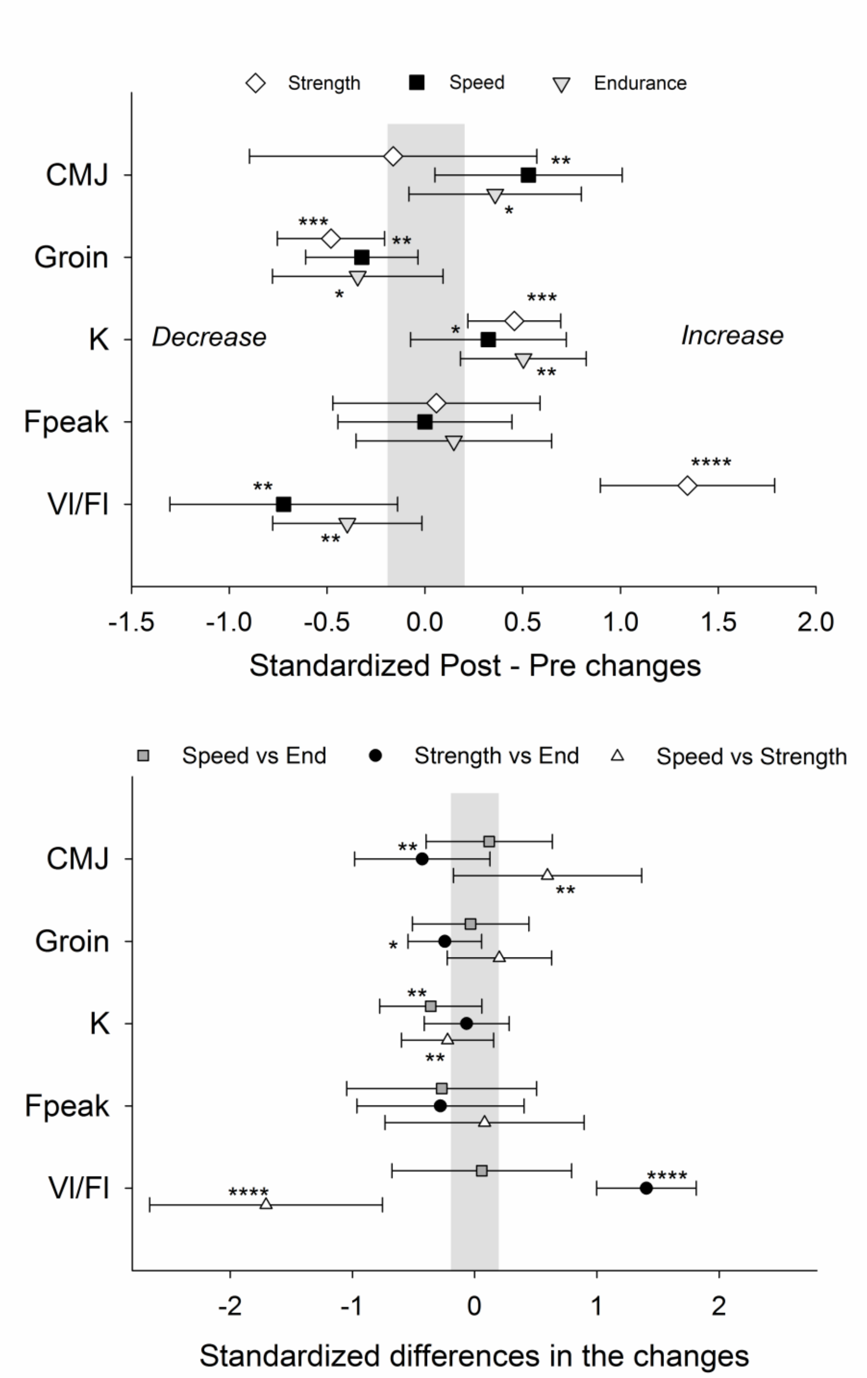

Figure 1. Upper panel: changes in counter movement jump (CMJ) and groin squeeze (Groin) performance, vertical stiffness (K), peak loading force (Fpeak) and velocity load/force load ratio (Vl/Fl) following the three conditioned sessions. Lower panel: difference in the changes in the latter variables between the different sessions. *: possible, **: likely, ***: very likely and ****: almost certain change/difference in the change.

Table 1. Conditioned training sessions.

Strength	***Endurance***	***Speed***
1. Progressive plyometric drills (10 min), 2. Strength stations (4 x 10-m lateral sprints with elastic bands, lateral lunges on a step + 5-m forward sprint, 6 single-leg forward hops + 5-m forward sprint, 5+5+5+5-m COD-sprint vs. opponent, 4 x 15-m PowerSprint[26] sprints – pulling equivalent of 24 kg[26]), 3. Technical warm-up (passing, 5 min), 4. Game simulation 4 vs. 4 + 2 goal keepers (width x depth, 30x25 m, three touches, 2x3 min, r=90 s). 5. Same as 4 but free touches and individual defense. 6. Same as 4 but increased verbal encouragement from the coach.	1. Continuous 10-12-km/h run including whole-body mobility (12 min), 2. Technical warm-up (passing, 8 min), 3. Game with two small goals 4 vs. 4 (40x35 m, three touches, 2x8 min, r=90 s). 4. Same as 3 but goal only valid if all team mates have crossed the middle line. 5. Same as 4 but free touches + increased verbal encouragement from the coach.	1. Running technique drills (10 min), 2. Technical warm-up (passing, 5 min), 3. Possession 8 vs. 8 (35x55 m, free touch, players need to receive the ball behind the goal line while not starting their run before the pass is initiated, 3x6 min, r=90 s). 4. Sprint running (3x10 m, 3x15 m flying, 3x15 m standing start vs. opponent, 2x20 m standing start vs. opponent, r=45 s), 5. Same as 3 but increased verbal encouragement from the coach and increased emphasis on counter-attacking.

Table 2. Reliability of generic and running-based indices of neuromuscular performance in the field.

	CMJ (cm)	*Groin Squeeze (N)*	*K ($kN.m^{-1}$)*	*Fpeak (N)*	*Vl/Fl (A.U)*
n *test-rest comparisons*	35	37	44	44	44
Average ± SD	41.5 ± 5	77 ± 16.5	28.3 ± 5.7	3968 ± 907	256 ± 25.7
TE as a CV% (90%CL)	5.4 (4.2;8.0)	4.8 (3.8;7.2)	11.0 (8.6;15.6)	17.1 (13.6;25.1)	7.2 (5.8;10.1)
Standardized TE (90%CL)	0.44 (0.35;0.64)	0.22 (0.18;0.33)	0.52 (0.68;1.20)	0.75 (0.60;1.06)	0.67 (0.54;0.94)
ICC	0.83 (0.64;0.93)	0.96 (0.90;0.98)	0.75 (0.52;0.88)	0.47 (0.12;0.72)	0.57 (0.26;0.78)
SWC	3%	4%	4%	5%	2%

SD: standard deviation. TE: typical error expressed as a coefficient of variation (CV, with 90% confidence intervals, CL). ICC: Intraclass correlation coefficient. SWC: smallest worthwhile change (0.2 between-player SD).

Table 3. Running and heart rate demands, and rate of perceived exertion for the three conditioned sessions.

	Strength	***Endurance***	***Speed***	***Paired comparisons***
Duration (min)	81	93	75	N/A
Total Distance (m)	4370 ± 193	7794 ± 598	5298 ± 420	All very large and almost likely
Total Distance (m/min)	54 ± 2	84 ± 6	71 ± 6	All very large and almost likely
Distance >19.8 km/h (m)	51 ± 12	73 ± 52	408 ± 106	All very large and almost likely but Strength vs. Endurance (possibly small)
Distance >25.2 km/h (m)	0 ± 0	5 ± 9	91 ± 28	All very large and almost likely
Peak Speed (km/h)	23.3 ± 0.9	25.0 ± 1.9	29.7 ± 1.5	All very large and almost likely but Strength vs. Endurance (very likely moderate)
Mechanical work (A.U)	49 ± 7	47 ± 11	50 ± 9	Speed vs. Endurance (possibly small)
Mechanical work (A.U/min)	0.6 ± 0.1	0.5 ± 0.1	0.7 ± 0.1	Strength vs. speed likely small, Speed vs. Aero almost likely very large and Strength vs. Endurance very likely large
Trimps (A.U)	463 ± 54	584 ± 49	436 ± 43	All very large and almost likely but Speed vs. Strength (likely small)
Time >90% HRmax	9 ± 12	16 ± 8	10 ± 8	Speed & Strength vs. Aero both likely small
RPE (A.U)	5.8 ± 0.9	5.7 ± 1.2	5.8 ± 0.8	None

N/A: not applicable. Trimps: training implus. HRmax/ maximal heart rate. RPE: rate of perceived exertion. Nb: the sessions do not include the ~7-min standardized exercise sequences.