Magnesium Status in Elite Track & Field Athletes: An 8-year Analysis of the British Athletics World Class Performance team

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Abstract

Magnesium plays a critical role in athlete health and performance. It is involved in numerous physiological mechanisms that support energy production, immune function, pain modulation, muscle function and bone health. Athletes may be susceptible to magnesium deficiency due to an increased utilisation during exercise.

Objective

This study reports on the magnesium status of 192 Olympic and Paralympic athletes over the course of eight years.

Methods

Athletes on the British Athletics world class performance plan undertook blood testing for Red Cell Magnesium status. Their history of tendon pain, muscle and bone injury, ethnicity, sporting event and gender were also recorded. 510 samples from 192 athletes were included in the study.

Results

On at least one blood test during the study time, 22% of athletes were identified as clinically deficient (<1.19 mmol/L). The average red cell magnesium concentration was 1.34 nmol/L. Magnesium was significantly lower in female athletes and those with Black or Mixed-Race ethnicity and was higher in Throws athletes and Paralympians with Cerebral Palsy. Athletes with a history of achilles or patella tendon pain had significantly lower magnesium levels than average.

Conclusions

This study highlights the importance of investigating magnesium within this population to identify deficiency and mitigate against potential performance reduction or increased injury risk. Several areas

for future work are identified to explore the relationship between magnesium and gender, ethnicity and tendon pain and muscle injury in athletes. Furthermore, new guidelines for magnesium status within athletics populations are proposed.

Key Words: Magnesium; Athletics; Sport; Performance; Tendon; Nutrition; Micronutrients

Introduction

Magnesium (Mg) is an intracellular mineral ion that plays a vital role in muscle function, bone metabolism and respiratory health [1]. Magnesium is involved in intracellular enzymatic reactions that drive protein synthesis and energy production [2], and it has an important role in immune function, recovery from oxidative stress and pain modulation [3,4]. As a result, Mg status is likely to be of importance in the athletic population for whom bone health and optimal muscular, immune and respiratory function is required for consistent training and athletic performance.

Magnesium has an important role in the maintenance of normal muscle contraction and relaxation[5], and Mg intake has been associated with improved muscle function and reduced sarcopenia in elderly populations and male athletes [6,7]. Magnesium also is an N-methyl-D-aspartate (NMDA) receptor antagonist and therefore may have an important role in pain transduction and hypersensitivity.[8] NMDA activation and upregulation is recognised in the central sensitisation associated with painful tendinopathy [9–11], although the specific role of Mg in tendon pain has not been previously investigated. Magnesium is also required for the conversion of 25(OH)D to its active form which supports calcium absorption and bone metabolism. Magnesium deficiency is directly associated with a negative impact on bone metabolism by decreasing osteoblastic and increasing osteoclastic activity [12–14]. Lower dietary Mg intake has been associated with reduced bone mineral density which is a risk factor for bone stress injury in athletes [15,16].

The Reference Nutrient Intakes (RNI) for Mg in the UK is 300 mg and 270 mg for males and females, respectively. Unlike other micronutrients, Mg is easily obtained in the diet from foods such as fruits and vegetables, dairy, and nuts and seeds. Despite this, Mg deficiency is not uncommon, with subclinical deficiency estimated at 40% in young adults [17]. Many athletes may not meet the recommended Mg

intakes [18–21] and Olympic athletes have significantly lower resting plasma Mg status compared with non-athletes [22].

Potential reasons for deficiency include diminished Mg intake via processed and boiled foods and reduced absorption in vitamin D deficient individuals [23]. Athletes may be predisposed to Mg deficiency as the recommended daily requirements are likely to be 10-20% higher than a sedentary population [4,24] due to increased requirements of Mg during exercise. Decreased Mg absorption is also associated with high fibre diets [25] which are often advocated by performance nutritionists. Furthermore, intense prolonged physical exercise increases Mg sweat loss and anaerobic exercise increases urinary Mg loss, possibly due to decreased tubular resorption [2,26–29]. A transient reduction in Mg after endurance running has also been identified, possibly due to a loss of muscle membrane integrity [28,30].

The correction of Mg deficiency has been associated with performance improvements in bench press, jump height, knee extension torque and cardiorespiratory function [7,27,31–33]. A recent review concluded that increased intakes of Mg will likely have beneficial effects on exercise performance in Mg deficient individuals.[4] However, the impact of Mg supplementation on physical performance in physically active individuals with adequate Mg status is uncertain.[5]

The assessment of Mg status is challenging as less than 1% of Mg in the body circulates within the blood, with more than 50% stored in bone and the remainder stored in cells within muscle tissue and organs [34]. As plasma and serum Mg are prone to fluctuations, diurnal, dietary and exercise induced, these markers are not considered as reliable indicators of Mg status [35]. Whole blood and red blood cell Mg (RCMg) are considered to be more accurate markers of long term Mg status as they are more stable and

118 can detect the depletion of cellular stores [36]. Ionised Mg (iMg) may be a useful marker of Mg status as
119 this is the active form of Mg, however methods of iMg analysis are limited and therefore not easily
120 accessible for regular analysis within athletics populations [30]. A gold standard method of status
121 assessment is the intravenous Mg loading test which detects the dose retained after Mg injection. This
122 requires a 24 h collection of urine and is an impractical test for mass screening of athletes. Due to the
123 challenges of assessing Mg status and the limited studies performed on athletes, the prevalence of Mg
124 deficiency in athletes, and indeed the appropriate range for athletes are both uncertain [37].
125
126 This study reports on the RCMg status of a cohort of British Olympic and Paralympic track and field
127 athletes over an eight year period and its association with gender, ethnicity, athletic event and clinical
128 history of bone stress, muscle injury and tendon pain.
129
130 **Materials and Methods**
131 All Track and Field athletes who formed part of the British World Class Performance Programme (WCPP)
132 between September 2010 and February 2017 were eligible for inclusion in this study. Athletes are only
133 included in the WCPP if they are considered by performance coaches to have potential to win a medal at
134 an Olympic or Paralympic Games due to their current level of athletic performance. Informed consent
135 was provided by all athletes at the point of joining the WCPP and the study was approved by the
136 University of Loughborough Ethics Committee.
137
138 Blood screening for RCMg status was conducted as part of general performance screening all athletes
139 between 2-4 times per year. These were always performed during athlete training phases between
140 October and August, when athletes were undertaking regular running and strength and conditioning
141 sessions. Blood screening was not taken during rest phases of the training cycle. Athletes were asked to

avoid high intensity strength and running training or competition for at least 12 h prior to the blood test but no other restrictions were placed on training. Subjects were not asked to fast prior to the test. Venepuncture was performed with a 21- or 23-gauge butterfly needle with the athlete seated or prone lying at 45 degrees and collected into a vacutainer (BD Vacutainer® lithium heparin blood collection tubes). All blood samples were analysed by The Doctor's Laboratory (TDL Ltd, London) using RCMg analysis. The analysis performed was inductively coupled plasma mass spectrometry (ICP-MS) with a known laboratory coefficient of variation of 2.5%. Demographic information including age, gender and athletic event was recorded.

A review of the British Athletics electronic medical record was performed and, due to the potential relationship with RCMg status, the presence of the following clinical conditions was recorded: a history of painful Achilles or Patella tendinopathy, defined as a greater than 3 month history of Achilles or Patella tendon pain that caused some modification to training; a history of bone stress injury; and number of muscle injuries in the same year of the test.

Data Analysis

In total, 510 blood samples were obtained from athletes across 8 years (from 2010-17) and used in the data analysis. The data had a hierarchically nested structure with blood samples (Level 1) nested within athletes (Level 2). As a result, we constructed a series of multilevel regression models to carry out the analysis using MLwiN software (version 2.34)[38]. Multilevel regression models account for this hierarchical data structure by modelling separate, but related equations at the within- and between-person levels. Multilevel modelling provides enormous flexibility when analysing longitudinal data, such that any analysis stays faithful to the true structure of the data. In this case we labelled the beginning of the study (September 2010) as zero, with each passing month labelled relative to this anchor (i.e.,

October 2010 = 1, November 2010 = 2, and so on). Therefore, there are no artificially created groups and the data point is accurately placed in time to the nearest month.

Prior to the substantive analysis, an intercept-only model was constructed (i.e., no predictor variables included) to explore the degree of variance in Mg attributable to the within- and between-athlete levels. That is, what percentage of variance in Mg can be associated with fluctuations within athletes or differences between athletes? Next, this baseline model was extended with the addition of a series of categorical predictor variables to examine gender (Female as the reference category), ethnicity (White as the reference category), type of athletic event (Power and Endurance as the reference categories, respectively), history of tendon pain (No history of AT/PT as the reference category), and diagnosis of Cerebral Palsy, as the largest disability group in the Paralympic program (No Cerebral Palsy as the reference category) as predictors of Mg. Using continuous predictor variables, clinical history (i.e. total number) of bone stress complications and muscle injuries as predictors of Mg was also assessed. The model examining type of event was only conducted on Olympic athletes due to the complexity and diversity of event classification in Paralympic sport. Only Olympic athletes were used for the analysis of history of AT/PT due to the low incidence of these injuries in Paralympic athletes. Each variable was examined in a separate model. By examining the regression coefficients and standard errors of each predictor variable within these equations, we calculated the predicted Mg for each sub-population (e.g., males, Black athletes, and so on), as well as the 95% confidence intervals.

Results

The data set comprises 510 samples taken from 192 athletes aged between 16-49 y (mean 24.2 ± 5.7 y). (Table 1.)

Sixty-nine samples from 42 athletes were noted to have magnesium deficiency, diagnosed as an RCMg level less than 1.19 mmol/L as predefined by the laboratory range. The average RCMg across the Olympic program was 1.34 ± 0.14 mmol/l.

The results of the multilevel regression models can be seen in Table 2. In the categorical variable models, the intercept refers to the predicted Mg level for the reference category (which are identified in the table). The regression coefficients refer to the difference in Mg between the reference category and the comparison category. In the continuous variable models (i.e., bone and muscle injuries), the intercept term refers to the predicted Mg level in athletes without any history of the injury. The regression coefficient reflects the predicted Mg status for every instance of the injury occurring. The random effects are displayed in the table should readers wish to evaluate all parameters in the models.
The variance terms in the intercept-only model revealed that 60 % of the variance in Mg was attributable to differences across athletes, and 40 % was attributable to fluctuations within athletes across time. Both variance terms were statistically significant ($p < 0.001$), justifying the use of multilevel modelling. Results of the conditional regression models revealed that Mg was higher in males compared to females ($b = .05$; $p = .01$). White athletes had higher Mg concentrations than Black athletes ($b = .08$; $p < .001$) and Mixed-Race athletes ($b = .07$; $p = .06$). A second model, testing ethnicity with Black athletes as the reference category, revealed no differences between Mixed Race and Black athletes ($b = .01$; $p = .71$).

Athlete Specific Observations

RCM status was higher in Throwers compared to Power athletes (b = .07; p = .02), with no differences observed between Endurance athletes and the other groups (Throwers: b = .04; p = .21; Power: b = - .03; p = .21). Paralympic athletes with cerebral palsy had higher levels of RCMg, relative to all other athletes (b = .09; p < .001)

Clinical History

The models investigating clinical history revealed that athletes with a history of tendon pain recorded lower RCMg, compared to athletes without history of tendon pain (b = -.05; p = .03). Every muscle injury sustained was associated with 0.01 mmol/L decreases in RCMg (95% CIs = 0.00 - 0.02, p = .05). Bone stress injuries were not associated with RCMg status (b = -.01; 95% CIs = -0.04 - 0.02, p = .48).

The predicted Mg levels of the sub-categories of athletes and associated 95% confidence intervals based on the multilevel regression equations described below (Fig. 1 and Table 2). These values account for the fact that some athletes' blood was sampled more times than other athletes, thus offering advantages over simple mean values.

Discussion

This is the first study to investigate RCMg status in a large group of elite athletes and reports an average RCMg status of 1.34 ± 0.14 mmol/L. The main findings are: 22% of athletes were found to have a Magnesium deficiency (<1.19mmol/l) during the study; higher levels of Magnesium in male athletes and those with white skin colour and athletes with Cerebral Palsy; and an association between low RCMg and a history of muscle injury or tendon pain.

Lower RCMg was associated with muscle injury rate over the course of this study. Mg deficiency has been associated with disrupted neuromuscular function, through central and peripheral mechanisms [5,39,40]. Energy production is dependent on cellular Mg status, as Mg has a key role in glucose metabolism.[41,42] Animal models have demonstrated that Mg supplementation increases muscle glucose availability and reduces lactate accumulation [43]. The accumulation of lactate, which may therefore be increased in Mg deficiency, may induce muscle fatigue which is a recognised risk factor for muscle injury [41,44]. Magnesium also has a key role in the regulation of cerebral glucose levels and therefore suboptimal Mg levels may reduce the central coordination of complex movements that require a high percentage of muscle recruitment and subsequently increase muscle injury risk in sprinting [43,45]. Further work is required to explore the role of Mg in muscle injury and in exercise associated muscle cramping which was beyond the scope of this study.

Magnesium status was also reported to be significantly lower in athletes with a history of achilles or patella tendon pain. Magnesium is known to play an important role in chronic pain[8,9] as an antagonist of the N-methyl-D-aspartate (NMDA) receptor, a receptor involved in the propagation of chronic pain [8]. Central sensitization appears to be an important mechanism in the presence of persistent pain in patients with tendinopathy [46–48]. NMDA receptors are also significantly elevated in the tendon tissue

of patients with chronically painful tendons [10]. Magnesium deficiency may be related to an upregulation of glutamate-NMDA signalling and related to tendon pain in athletes.

It is known that Mg absorption is reduced in individuals with Vitamin D deficiency. [49] Furthermore, it is commonly reported that Vitamin D deficiency is more prevalent in black athletes [50] due to reduced absorption of Vitamin D in those with darker skin pigment.[51,52] Within the current study, RCMg status was reported to be significantly lower in Black and Mixed-Race athletes relative to White athletes. Furthermore, RCMg levels were higher in males compared with females and this pattern is also noted with Vitamin D deficiency [50]. Further work into the relationship between Vitamin D and Magnesium should be explored and screening of Magnesium status in athletes with low Vitamin D is advisable[53].

A few notable discipline-specific observations include RCMg levels as higher in Throws athletes compared with Sprint and Jumps athletes. No differences were reported between Endurance athletes and other disciplines. Future work investigating RCMg status across a wide range of athletic disciplines would help to establish if RCMg status is impacted by the nature of the sporting discipline or by alternative, but associated factors, such as body composition, total training load, aerobic vs anaerobic metabolism or predominant muscle fibre type.

A novel finding of this study was that Mg levels were significantly higher in athletes with Cerebral Palsy (CP). This has not been noted in any previous work. This may relate to the relative reduction in total muscle mass and/or levels muscle contraction and activation in athletes with CP, thus decreasing Mg utilisation [54]. Muscles in patients with CP are also noted to have an increase in extracellular matrix and reduced contractile tissue which would potentially reduce Mg utilisation [55]. Further work in the area of CP muscle physiology, particularly in regard to athletic performance is required.

286

287 Practical dietary strategies to help athletes increase intakes of Mg should be employed before
288 supplementation is considered. Dietary sources of Mg can be found in foods such as; nuts, seeds, green
289 leafy vegetables, fish, beans and wholegrains. The timing of ingestion of Magnesium-rich foods may be
290 an important factor for athletes to consider. It is reported that plasma Mg status transiently decreases
291 during exercise, before returning to baseline values within 2.5 h of exercise cessation [30]. Unpublished
292 preliminary data from our laboratory has demonstrated that pre-loading athletes with 250 mg Mg 1 h
293 prior to 30 min treadmill running at 75 % VO_{2max} prevented a fall in plasma Mg status. The repeated
294 fluctuations in plasma Mg status caused by the rigorous training regimes of elite athletes may attenuate
295 the risk of chronically low RCMg status.

296

297 However, there are some limitations of the study of 192 elite track and field athletes over eight years.
298 While all athletes had the support of the team nutritionist, regular, consistent dietary analyses were not
299 performed on all athletes. This may limit conclusions with respect to the impact of exercise type or
300 other variables on Mg status, as Mg intake or supplementation was not controlled. While athletes were
301 recommended to avoid heavy training prior to their blood tests, the pre-test conditions were not
302 carefully controlled. While all athletes were in training, overall load, hydration status, nutritional intake
303 or specific training sessions were not standardised prior to each screen which may limit conclusions,
304 although this is the nature of working with individual elite athletes. However, the large number of
305 samples; the use of RCMg for analysis, which is more stable and less prone to diurnal fluctuation than
306 plasma or serum Mg; and the longevity of the study adds support to the validity of the findings. In
307 addition, this is an elite athlete group which will assist clinicians in the practical application of this study
308 to other athlete groups.

309

This study is the first to report the prevalence of Mg deficiency in a large cohort of elite athletes. The observed associations between Mg status and soft-tissue related issues suggest that the monitoring of Mg status and the treatment of Mg insufficiency to improve athlete health and performance should form part of regular sports nutrition and medicine screening. Due to a paucity of data within athletic populations, normal ranges for RCMg status and considerations around athlete-specific sufficiency, insufficiency and deficiency guidelines are yet to be established. Based on the findings of this study, predicted RCMg status and the potential importance of RCMg and until further work is performed, the authors suggest the following RCMg guidelines for clinicians working with elite athletes; Optimal: >1.34mmol/l, Suboptimal:1.30-1.34mmol/l; Insufficient: 1.25-1.30mmol/L and Deficient: <1.25mmol/l. Magnesium is an important, and potentially undervalued, mineral in athletic performance and further work is required to understand the impact of Mg status and supplementation in this population with respect to health, injury and performance.

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References

1. Kew KM, Kirtchuk L, Michell CI. Intravenous magnesium sulfate for treating adults with acute asthma in the emergency department. Cochrane Database Syst Rev. 2014 May 28;(5):CD010909.

2. Newhouse IJ, Finstad EW. The effects of magnesium supplementation on exercise performance. Clin J Sport Med Off J Can Acad Sport Med. 2000 Jul;10(3):195–200.

3. Crosby V, Wilcock A, Corcoran R. The safety and efficacy of a single dose (500 mg or 1 g) of intravenous magnesium sulfate in neuropathic pain poorly responsive to strong opioid analgesics in patients with cancer. J Pain Symptom Manage. 2000 Jan;19(1):35–9.

4. Nielsen FH, Lukaski HC. Update on the relationship between magnesium and exercise. Magnes Res. 2006 Sep;19(3):180–9.

5. Zhang Y, Xun P, Wang R, Mao L, He K. Can Magnesium Enhance Exercise Performance? Nutrients [Internet]. 2017 Aug 28;9(9). Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5622706/

6. van Dronkelaar C, van Velzen A, Abdelrazek M, van der Steen A, Weijs PJM, Tieland M. Minerals and Sarcopenia; The Role of Calcium, Iron, Magnesium, Phosphorus, Potassium, Selenium, Sodium, and Zinc on Muscle Mass, Muscle Strength, and Physical Performance in Older Adults: A Systematic Review. J Am Med Dir Assoc. 2018 Jan;19(1):6–11.e3.

7. Santos DA, Matias CN, Monteiro CP, Silva AM, Rocha PM, Minderico CS, et al. Magnesium intake is associated with strength performance in elite basketball, handball and volleyball players. Magnes Res. 2011 Dec;24(4):215–9.

8. Na H-S, Ryu J-H, Do S-H. The role of magnesium in pain. In: Vink R, Nechifor M, editors. Magnesium in the Central Nervous System [Internet]. Adelaide (AU): University of Adelaide Press; 2011. Available from: http://www.ncbi.nlm.nih.gov/books/NBK507245/

9. Srebro D, Vučković S, Milovanović A, Košutić J, Vujović KS, Prostran M. Magnesium in pain research: state of the art. Curr Med Chem. 2016 Dec 12;

10. Schizas N, Lian Ø, Frihagen F, Engebretsen L, Bahr R, Ackermann PW. Coexistence of up-regulated NMDA receptor 1 and glutamate on nerves, vessels and transformed tenocytes in tendinopathy. Scand J Med Sci Sports. 2010 Apr;20(2):208–15.

11. Spang C, Backman LJ, Le Roux S, Chen J, Danielson P. Glutamate signaling through the NMDA receptor reduces the expression of scleraxis in plantaris tendon derived cells. BMC Musculoskelet Disord. 2017 May 25;18(1):218.

12. Musso CG. Magnesium metabolism in health and disease. Int Urol Nephrol. 2009;41(2):357–62.

13. Rude RK, Gruber HE, Wei LY, Frausto A, Mills BG. Magnesium deficiency: effect on bone and mineral metabolism in the mouse. Calcif Tissue Int. 2003 Jan;72(1):32–41.

14. Rude RK, Gruber HE, Norton HJ, Wei LY, Frausto A, Kilburn J. Reduction of dietary magnesium by only 50% in the rat disrupts bone and mineral metabolism. Osteoporos Int J Establ Result Coop Eur Found Osteoporos Natl Osteoporos Found USA. 2006;17(7):1022–32.

15. Orchard TS, Larson JC, Alghothani N, Bout-Tabaku S, Cauley JA, Chen Z, et al. Magnesium intake, bone mineral density, and fractures: results from the Women's Health Initiative Observational Study. Am J Clin Nutr. 2014 Apr;99(4):926–33.

16. Farsinejad-Marj M, Saneei P, Esmaillzadeh A. Dietary magnesium intake, bone mineral density and risk of fracture: a systematic review and meta-analysis. Osteoporos Int J Establ Result Coop Eur Found Osteoporos Natl Osteoporos Found USA. 2016 Apr;27(4):1389–99.

17. Hermes Sales C, Azevedo Nascimento D, Queiroz Medeiros AC, Costa Lima K, Campos Pedrosa LF, Colli C. There is chronic latent magnesium deficiency in apparently healthy university students. Nutr Hosp. 2014 Jul 1;30(1):200–4.

18. Imamura H, Iide K, Yoshimura Y, Kumagai K, Oshikata R, Miyahara K, et al. Nutrient intake, serum lipids and iron status of colligiate rugby players. J Int Soc Sports Nutr. 2013 Feb 13;10(1):9.

19. Juzwiak CR, Amancio OMS, Vitalle MSS, Pinheiro MM, Szejnfeld VL. Body composition and nutritional profile of male adolescent tennis players. J Sports Sci. 2008 Sep;26(11):1209–17.

20. Wierniuk A, Włodarek D. Estimation of energy and nutritional intake of young men practicing aerobic sports. Rocz Panstw Zakl Hig. 2013;64(2):143–8.

21. Noda Y, Iide K, Masuda R, Kishida R, Nagata A, Hirakawa F, et al. Nutrient intake and blood iron status of male collegiate soccer players. Asia Pac J Clin Nutr. 2009;18(3):344–50.

22. Killer SC, Brown RA, Collins AL. Magnesium status in Olympic & Paralympic athletes compared with a sedentary population and validation of a FFQ as an assessment tool for dietary magnesium intake. Unpublished [Internet]. 2016; Available from: http://rgdoi.net/10.13140/RG.2.2.27789.95207

23. Krejs GJ, Nicar MJ, Zerwekh JE, Norman DA, Kane MG, Pak CY. Effect of 1,25-dihydroxyvitamin D3 on calcium and magnesium absorption in the healthy human jejunum and ileum. Am J Med. 1983 Dec;75(6):973–6.

24. Buchman AL, Keen C, Commisso J, Killip D, Ou CN, Rognerud CL, et al. The effect of a marathon run on plasma and urine mineral and metal concentrations. J Am Coll Nutr. 1998 Apr;17(2):124–7.

25. Bohl CH, Volpe SL. Magnesium and exercise. Crit Rev Food Sci Nutr. 2002;42(6):533–63.

26. Rose LI, Carroll DR, Lowe SL, Peterson EW, Cooper KH. Serum electrolyte changes after marathon running. J Appl Physiol. 1970 Oct;29(4):449–51.

27. Brilla LR, Haley TF. Effect of magnesium supplementation on strength training in humans. J Am Coll Nutr. 1992 Jun;11(3):326–9.

28. Stendig-Lindberg G, Shapiro Y, Epstein Y, Galun E, Schonberger E, Graff E, et al. Changes in serum magnesium concentration after strenuous exercise. J Am Coll Nutr. 1987 Feb;6(1):35–40.

29. Nuviala RJ, Lapieza MG, Bernal E. Magnesium, zinc, and copper status in women involved in different sports. Int J Sport Nutr. 1999 Sep;9(3):295–309.

30. Terink R, Balvers MGJ, Hopman MT, Witkamp RF, Mensink M, Gunnewiek JMTK. Decrease in Ionized and Total Magnesium Blood Concentrations in Endurance Athletes Following an Exercise Bout Restores Within Hours - Potential Consequences for Monitoring and Supplementation. Int J Sport Nutr Exerc Metab. 2016 Dec 20;1–22.

31. Kass LS, Poeira F. The effect of acute vs chronic magnesium supplementation on exercise and recovery on resistance exercise, blood pressure and total peripheral resistance on normotensive adults. J Int Soc Sports Nutr. 2015;12:19.

32. Matias CN, Santos DA, Monteiro CP, Silva AM, Raposo M de F, Martins F, et al. Magnesium and strength in elite judo athletes according to intracellular water changes. Magnes Res. 2010 Sep;23(3):138–41.

33. Setaro L, Santos-Silva PR, Nakano EY, Sales CH, Nunes N, Greve JM, et al. Magnesium status and the physical performance of volleyball players: effects of magnesium supplementation. J Sports Sci. 2014;32(5):438–45.

34. Speich M, Pineau A, Ballereau F. Minerals, trace elements and related biological variables in athletes and during physical activity. Clin Chim Acta Int J Clin Chem. 2001 Oct;312(1–2):1–11.

35. Volpe SL. Magnesium and the Athlete. Curr Sports Med Rep. 2015 Aug;14(4):279–83.

36. Witkowski M, Hubert J, Mazur A. Methods of assessment of magnesium status in humans: a systematic review. Magnes Res. 2011 Dec;24(4):163–80.

37. Malliaropoulos N, Tsitas K, Porfiriadou A, Papalada A, R Ames P, Del Buono A, et al. Blood phosphorus and magnesium levels in 130 elite track and field athletes. Asian J Sports Med. 2013 Mar;4(1):49–53.

38. Hox J. Multilevel analysis: Techniques and applications. 2nd ed. NY: Routledge/Taylor & Francis Group; 2010.

39. Cheng S-M, Yang L-L, Chen S-H, Hsu M-H, Chen I-J, Cheng F-C. Magnesium sulfate enhances exercise performance and manipulates dynamic changes in peripheral glucose utilization. Eur J Appl Physiol. 2010 Jan;108(2):363–9.

40. Liu L, Borowski G, Rose LI. Hypomagnesemia in a Tennis Player. Phys Sportsmed. 1983 May;11(5):79–80.

41. Cheng S-M, Yang L-L, Chen S-H, Hsu M-H, Chen I-J, Cheng F-C. Magnesium sulfate enhances exercise performance and manipulates dynamic changes in peripheral glucose utilization. Eur J Appl Physiol. 2010 Jan;108(2):363–9.

42. Yamanaka R, Tabata S, Shindo Y, Hotta K, Suzuki K, Soga T, et al. Mitochondrial Mg(2+) homeostasis decides cellular energy metabolism and vulnerability to stress. Sci Rep. 2016 26;6:30027.

43. Chen H-Y, Cheng F-C, Pan H-C, Hsu J-C, Wang M-F. Magnesium enhances exercise performance via increasing glucose availability in the blood, muscle, and brain during exercise. PloS One. 2014;9(1):e85486.

44. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Epidemiology of injuries in English professional rugby union: part 1 match injuries. Br J Sports Med. 2005 Oct;39(10):757–66.

45. Cheng S-M, Yang D-Y, Lee C-P, Pan H-C, Lin M-T, Chen S-H, et al. Effects of magnesium sulfate on dynamic changes of brain glucose and its metabolites during a short-term forced swimming in gerbils. Eur J Appl Physiol. 2007 Apr;99(6):695–9.

46. Rio E, Kidgell D, Moseley GL, Cook J. Elevated corticospinal excitability in patellar tendinopathy compared with other anterior knee pain or no pain. Scand J Med Sci Sports. 2016 Sep;26(9):1072–9.

47. van Wilgen CP, Konopka KH, Keizer D, Zwerver J, Dekker R. Do patients with chronic patellar tendinopathy have an altered somatosensory profile? A Quantitative Sensory Testing (QST) study. Scand J Med Sci Sports. 2013 Mar;23(2):149–55.

48. Plinsinga ML, Brink MS, Vicenzino B, van Wilgen CP. Evidence of Nervous System Sensitization in Commonly Presenting and Persistent Painful Tendinopathies: A Systematic Review. J Orthop Sports Phys Ther. 2015 Nov;45(11):864–75.

49. Schwalfenberg GK, Genuis SJ. Vitamin D, Essential Minerals, and Toxic Elements: Exploring Interactions between Nutrients and Toxicants in Clinical Medicine. ScientificWorldJournal. 2015;2015:318595.

50. Pollock N, Dijkstra P, Chakraverty R, Hamilton B. Low 25(OH) vitamin D concentrations in international UK track and field athletes. South Afr J Sports Med [Internet]. 2012 [cited 2015 Mar 3];24(2). Available from: http://www.ajol.info/index.php/sasma/article/view/78022

51. Brown LL, Cohen B, Tabor D, Zappalà G, Maruvada P, Coates PM. The vitamin D paradox in Black Americans: a systems-based approach to investigating clinical practice, research, and public health - expert panel meeting report. BMC Proc. 2018;12(Suppl 6):6.

52. Webb AR, Kazantzidis A, Kift RC, Farrar MD, Wilkinson J, Rhodes LE. Colour Counts: Sunlight and Skin Type as Drivers of Vitamin D Deficiency at UK Latitudes. Nutrients. 2018 Apr 7;10(4).

53. Dai Q, Zhu X, Manson JE, Song Y, Li X, Franke AA, et al. Magnesium status and supplementation influence vitamin D status and metabolism: results from a randomized trial. Am J Clin Nutr. 2018 Dec 1;108(6):1249–58.

54. Hussain AW, Onambele GL, Williams AG, Morse CI. Muscle size, activation, and coactivation in adults with cerebral palsy. Muscle Nerve. 2014 Jan;49(1):76–83.

55. Lieber RL, Runesson E, Einarsson F, Fridén J. Inferior mechanical properties of spastic muscle bundles due to hypertrophic but compromised extracellular matrix material. Muscle Nerve. 2003 Oct;28(4):464–71.

Table 1: Sample size for each sub-group of athletes

Characteristic:		Number of athletes
Gender	Male	104
	Female	88
Ethnicity	White	113
	Black	51
	Mixed Race	13
	Unreported	15
Discipline:		
Olympic	Sprint/Power	85

	Endurance	39
	Throws	19
Paralympic Classification	Cerebral Palsy	25
	Spinal Injury	12
	Amputation	9
	Other	3
Clinical History:		
	Tendon Pain	52
	Bone Stress Injury	12
	Muscle Injury	84

Table 2: Multilevel Regression Models Examining Predictors of Mg Status

	Multilevel regression model (Coefficients are followed by standard errors are parentheses							
Predictor Variable	Intercept Only	Gender	Ethnicity	Ethnicity 2	Type of Event	Type of Event 2	Muscle Injury	Bone Injury
Fixed Effects								
Intercept	1.36(.01)	1.33(.01)	1.38(.01)	1.30(.02)	1.32(.02)	1.35(.02)	1.37(.01)	1.36(
Gender (Female as ref category)		.05(.02)						
Black Ethnicity (White as ref category)			-.08(.02)					
Mixed Race Ethnicity (White as ref category)			-.07(.04)					

White Ethnicity (Black as ref category)				.08(.02)				
Mixed Race Ethnicity (Black as ref category				.01(.04)				
Endurance Event (Power events as ref category)					.03(.02)			
Throws Event (Power events as ref category)					.07(.03)			
Power Event (Endurance events as ref category)						-.03(.02)		
Throws Event (Endurance events as ref category)						.04(.03)		
Number of muscle injuries							-.01(.005)	
Number of bone injuries								-.01(.
Random Effects								
Intercept	.012(.002)	.011(.002)	.010(.002)	.010(.002)	.010(.002)	.010(.002)	.011(.002)	.012(.
Level 1 error	.008(.001)	.008(.001)	.008(.001)	.008(.001)	.008(.001)	.008(.001)	.008(.001)	.008(.

Table 3: Regression-based predicted RCMg levels and 95% confidence intervals (*statistically significant differences between categories $p < .05$).

	Regression-based predicted Mg (mmol/L)	95% confidence intervals
Whole Sample	1.36	1.34 – 1.38
Gender		

Males	1.38*	1.36 – 1.40
Females	1.33	1.30 – 1.36
Ethnicity		
White	1.38*	1.36 – 1.40
Black	1.30	1.27 – 1.34
Mixed Race	1.32	1.25 – 1.38
Event Category		
Throwers	1.39*	1.33 – 1.45
Power	1.32	1.29 – 1.35
Endurance	1.35	1.31 – 1.39
Cerebral Palsy		
Yes	1.44*	1.39 – 1.49
No	1.35	1.33 – 1.37
Tendon Pain History		
Yes	1.31*	1.27 – 1.34
No	1.35	1.33 – 1.38

Fig. 1 Mean and 95% confidence levels for RCMg for subgroups (*p<0.05)