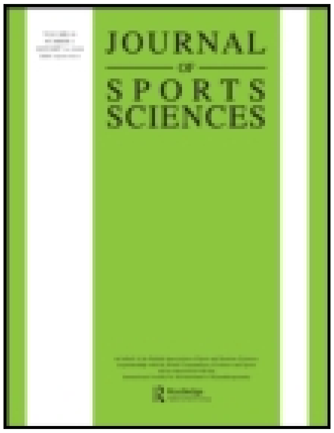

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Magnesium status and the physical performance of volleyball players: effects of magnesium supplementation

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Magnesium status and the physical performance of volleyball players: effects of magnesium supplementation

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Abstract
The aim of this study was to test the hypothesis that magnesium supplementation influences the physical performance of volleyball players, as the efficacy of this approach remains questionable. Twenty-five professional male volleyball players were assigned randomly to experimental (350 mg Mg · d^{-1}, 4 weeks) and control groups (500 mg maltodextrin · d^{-1}, 4 weeks) maintaining inter-group homogeneity of urinary magnesium. Erythrocyte, plasma and urinary magnesium levels, plasma creatine kinase activity, lactate production, maximal oxygen uptake (VO_2 max) and plyometric (squat jump, countermovement jump, countermovement jump with arm swing) and isokinetic (peak torque, potency and total work) performances were evaluated before (T_0) and after (T_1) supplementation. Levels of erythrocyte and urinary magnesium and creatine kinase activity and VO_2 max remained within normal ranges in both groups. Plasma magnesium decreased significantly only within the experimental group. Significant decreases in lactate production and significant increases (of up to 3 cm) in countermovement jump and countermovement jump with arm swing values were detected in the experimental group following magnesium supplementation, but not in the control group at T_1. It is concluded that magnesium supplementation improved alactic anaerobic metabolism, even though the players were not magnesium-deficient.

Keywords: *athletes, magnesium supplementation, physical performance, vertical jump, volleyball*

Introduction

The application of various dietary supplements to improve athletic performance has increased during recent years. However, the necessity of such supplementation and its effectiveness in enhancing physical activity in sportsmen and athletes remains somewhat questionable. A number of studies have established a distinct relationship between physical performance and magnesium (Mg) concentrations (Cinar, Nizamlioglu, & Mogulkoc, 2006; Cinar, Polat, Mogulkoc, Nizamlioglu, & Baltaci, 2008; Lukaski, Bolonchuk, Klevay, Milne, & Sandstead, 1983; Santos et al., 2011; Setaro, Greve, Nakano, Correia, & Colli, 2008), while others demonstrated that compartmental changes in the levels of plasma and serum Mg are associated with the type of exercise undertaken (Bohl & Volpe, 2002; Nielsen & Lukaski, 2006). In general, Mg concentration increases with exhaustion after high-intensity exercises of short duration, but diminishes with exhaustion after high-intensity exercises of long duration (Rayssiguier, Guezennec, & Durlach, 1990). Furthermore, some studies revealed that athletes with inadequate Mg intake showed increased urinary excretion and explained the phenomenon as a temporary condition produced by physical exercise. In addition, it has been demonstrated that serum Mg and urinary excretion of the mineral diminished significantly after physical activity, suggesting a possible redistribution or depletion of Mg caused by greater demand for muscular work (Buchman et al., 1998; Speich, Pineau, & Ballereau, 2001)

The anaerobic alactic phosphogenic pathway is very important for movements of short duration

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and high intensity such as volleyball. Hence, Mg supplementation has been recommended for improving physical performance since this mineral is a cofactor for creatine kinase in the muscle, although it is not clear if such dietary increment really boosts the activity of the enzyme. So far the results of experiments involving Mg supplementation to athletes have been contradictory. Moreover, most studies do not provide data regarding the intake of Mg, thus rendering it difficult to draw conclusions since the effects of supplementation may vary among individuals with different dietary profiles.

In volleyball, efficient performance in vertical jumping is considered one of the key attributes required of elite players (Thissen-Milder & Mayhew, 1990) since this activity is involved in most offensive and defensive movements. The vertical jump demands considerable aerobic power and muscular endurance and is characterised by eccentric and concentric muscular action.

In order to test the hypothesis that Mg supplementation influences the physical performance of volleyball players, the Mg status of professional players was assessed before and after supplementation with magnesium oxide, and the influence of supplementation on muscle strength and power was evaluated.

Methods

Study population

The study was approved by the University Ethical Committee. The aims and objectives of the study were explained to all potential participants, and it was emphasised that participation was entirely voluntary. Written informed consent was obtained from each participant before to the commencement of the study.

The study population consisted of 25 professional male volleyball players within the age range of 15 to 20 years, comprising 14 from the junior-youth team and 11 from the youth team. Since all of the players participated in national competitions, the study was conducted during their training period. The players were trained for an average of 6 h · d^{-1}; they performed 2 h of muscle and tendon exercises and 4 h of work on court to improve agility, speed, balance, coordination and impulsion.

Treatment groups

The double-blind experiment was designed considering urinary Mg concentration as the parameter for homogenisation of the sample population. In order to distribute participants into groups, individuals were listed according to increasing level of urinary Mg (determined as described below). From the pair of participants presenting the lowest Mg concentrations, one was selected by random draw (performed by an independent researcher) to join the treatment group, while the other was assigned to the control group. This selection process was repeated for all other participants taken pairwise, with the remaining individual being assigned to the control group. The study was conducted over a period of 4 weeks, during which time the experimental group (n = 12) received 584 mg (2 × 292 mg · $capsule^{-1}$) of Mg oxide · d^{-1}, a dose corresponding to 350 mg of Mg · d^{-1}, while the control group (n = 13) received 500 mg (2 × 250 mg · $capsule^{-1}$) of maltodextrin · d^{-1}. The sample size was defined as a problem of two independent groups of participants with paired observations on each participant (Lachin, 1981) and considering differences greater than 2.7 cm as a critical difference for countermovement jump (Sheppard et al., 2010). Under a two-way repeated measures design and adopting a power of 90%, this sample size considers this critical difference statistically significant at the 5% level of significance.

Anthropometry

Anthropometric measurements were performed at the commencement of the study by the coach at the training site with the players bare footed and wearing only shorts. Body weight was determined using digital scales (Fillizola®, São Paulo, SP, Brazil) and height was measured with a stadiometer. Skinfold measurements at the chest, abdomen and thigh were obtained with a caliper (Lange®, Cambridge, MD, USA), while thigh, arm and forearm circumferences were estimated with a non-extendible tape. Body density was estimated from skinfold measurements according to the proposal of Jackson and Pollock (1978), and the value obtained was applied in the calculation of body fat percentage using the method of Siri (1961).

Evaluation of biochemical parameters

All biochemical evaluations were performed in triplicate before and after supplementation of Mg or maltodextrin. Participants were subjected to at least 12 h of fasting, following which blood sampling was performed by a trained nurse with athletes seated in a blood draw chair in a predetermined postural position. Aliquots (5 mL) of blood were collected by venipuncture using BD Vacutainer® (Franklin Lakes, NJ, USA) tubes containing anticoagulant (sodium citrate). Plasma Mg and erythrocyte Mg were measured by flame atomic absorption spectrometry (AAnalyst 100; Perkin Elmer, Norwalk, CT, USA), according to previously standardised and validated protocols (Sales, Rocha, Setaro, & Colli, 2012). Plasma creatine kinase activity was assayed using Labtest Diagnostica® (Lagoa Santa, MG, Brazil) laboratory kits according to a standard colorimetric method (Szasz, Gruber, & Bernt, 1976).

For the collection of 24-h urine samples, participants were provided with demineralised flasks (2 L) containing 50 mL of 3 mM hydrochloric acid to help preserve the urine and to prevent precipitation of Mg. The flasks were weighed using analytical scales both before and after urine collection. Urinary Mg was determined according to a modified version of a published method (Nicoll, Struthers, & Fraser, 1991; Ryan & Barbour, 1998) following a validation protocol developed in our laboratory. Urinary creatinine was assayed by the Jaffe reaction using Celm® laboratory kit (Barueri, SP, Brazil), and the results were expressed in mol Mg · mol^{-1} creatinine.

The precision of the methods was verified using secondary standards (biological sample pools) prepared in our laboratory. The intra- and inter-imprecision obtained for each metabolite assessed were, respectively, 4.1% and 2.7% for erythrocyte magnesium; 4.6% and 2.1% for plasma magnesium; 1.6% and 10.2% for urinary magnesium excretion; 2.3% and 2.7% for plasma creatinine kinase; and 4.5% and 5.8% for lactate.

Evaluation of physical performance

All evaluations were performed in triplicate before and after supplementation of Mg or maltodextrin.

Maximal oxygen uptake. VO_2 max values were determined using an Inbramed model ATL 10.200 ergometric treadmill (Porto Alegre, RS, Brazil) at a fixed inclination of 3% according to a modified version of a published protocol (Santos-Silva, Fonseca, Castro, Greve, & Hernandez, 2007). Before the exercise, players rested for 1 min and then warmed up at speeds of 4.8, 6.0 and 7.2 km · h^{-1} for 1 min each. The test commenced at a speed of 8.4 km · h^{-1}, and this was increased at a rate of 1.2 km · h^{-1} every 2 min until complete exhaustion.

Plyometrics. Neuromuscular capabilities were evaluated through plyometric exercises including the squat jump, the countermovement jump and the countermovement jump with arm swing (Bosco, Luhtanen, & Komi, 1983). The tests were supervised by the team coach and conducted in the Multisport Gymnasium using a Boscosystem (S. Rufina di Cittaducale, RI, Italy) Ergo Jump™ platform. Each player performed three jump attempts, and the mean values of jump height (cm) and time (ms) of triplicate measurements were calculated.

Isokinetic dynamometry. Dynamic muscle functions were assessed through isokinetic tests conducted using a Biodex Medical Systems (New York, NY, USA) System Pro® dynamometer. Before the tests, players warmed up for 5 min on an unloaded ergometric bicycle, following which isokinetic tests were performed in triplicate at angular velocities of 1.05, 3.14 and 5.24 rad · s^{-1} (Dvir, 1995; Gross, Credle, Hopkins, & Kollins, 1990). The parameters evaluated were peak torque (Nm), potency (W), work/body weight (%) and total work (J) of the muscle flexors and extensors of the right and left knees. The tests were supervised by the team coach.

Evaluation of lactate production

Production of lactate was determined at peak exercise by reflectance photometry according to a lactate oxidase-based method using a Boehringer-Mannheim (Ingelheim, Germany) Accusport portable lactate analyser.

Statistical analyses

Data were analysed using the Statistical Package for the Social Sciences (SPSS) for Windows software version 14.0. All variables (means ± standard deviations) determined for the control and experimental groups were compared before and after supplementation. Normality of distribution was verified using the Kolmogorov–Smirnov test, while statistical differences were evaluated using two-way repeated measures analysis of variance (ANOVA) with time (before × after supplementation) as within-participant factor and group (experimental × control group) as between-participant factor. Isokinetic parameters of the right and left knees were compared using paired Student's *t*-tests. All tests were performed considering bilateral alternative hypotheses and a level of significance of 5% ($P < 0.05$).

Results

The anthropometric characteristics and urinary Mg levels of the study population of volleyball players determined at the commencement of the study are shown in Table I. There were no significant differences between the control (n = 13) and the experimental (n = 12) groups in respect of any of the studied parameters.

Mean values of erythrocyte Mg of the control and experimental groups remained constant between before and after supplementation and were >5.10 μmol Mg · g^{-1} Hb (124 μg Mg · g^{-1} Hb) within the study period (Table II). Mean plasma Mg concentrations decreased between before and after supplementation in both groups, although the

Table I. Anthropometric characteristics and urinary Mg values of volleyball players (N = 25) before to supplementation treatments.

Variable	Control group (n = 13)	Experimental group (n = 12)
Age (year)	17.85 ± 0.99	17.42 ± 1.56
Body weight (kg)	82.9 ± 7.8	83 ± 9.5
Height (cm)	195.7 ± 8.9	191.4 ± 9.0
Body fat (%)	10 ± 4.4	11.6 ± 4.3
Fat mass (kg)	8.3 ± 4.0	9.7 ± 3.9
Lean mass (kg)	74.5 ± 7.7	73.3 ± 8.7
Urinary Mg ($mmol \cdot d^{-1}$)	5.04 ± 2.05	4.23 ± 1.57

Notes: Data represent mean values ± standard deviations. No statistical differences were observed between groups (Student's t-test; all $P < 0.05$).

reduction was significant only in the experimental group ($P < 0.03$). Mean urinary Mg levels and plasma creatine kinase activities were within the reference ranges at before and after in both groups.

There were no statistical differences in the mean VO_2 max values within or between the control and experimental groups at before and after supplementation (Table III). In contrast, the production of lactate at peak exercise by members of the experimental group decreased significantly following Mg supplementation. The countermovement jump and countermovement jump with arm swing values of players within the experimental group increased significantly at after supplementation period, while those of the control group remained unaffected.

Table II. Biochemical characteristics of volleyball players (N = 25) before (T_0) and after (T_1) supplementation of Mg (experimental group) or placebo (control group).

Variable	Reference value	Control group (n = 13) T_0	Control group (n = 13) T_1	P^a Intra	Experimental group (n = 10) T_0	Experimental group (n = 10) T_1	P^a Intra	P^b Inter
Erythrocyte Mg (μmol $Mg \cdot g^{-1}$ Hb)	>5.10[c]	6.15 ± 1.45	6.25 ± 1.33	0.799	6.07 ± 1.09	5.77 ± 0.88	0.532	0.511
Plasma Mg (mmol $Mg \cdot L^{-1}$)	0.64–1.04[c]	0.90 ± 0.17	0.82 ± 0.07	0.115	0.99 ± 0.20	0.85 ± 0.07	0.035	0.350
Urinary Mg (mol $Mg \cdot mol^{-1}$ creatinine)	0.28–0.43[c]	0.29 ± 0.1	0.27 ± 0.2	0.754	0.28 ± 0.1	0.37 ± 0.2	0.170	0.200
Plasma creatine kinase (U/L)	0–780[d]	640 ± 59	555.4 ± 604.8	0.434	579 ± 509.6	496.8 ± 346.1	0.593	0.989

Notes: Data represent mean values ± standard deviations.
[a]Two-way repeated measures ANOVA with time ($T_0 \times T_1$) as within-participant factor were performed to establish the significances of intra-group differences ($P < 0.05$).
[b]Two-way repeated measures ANOVA with group (control × experimental groups) as between-participant factor were performed to establish the significances of inter-group differences ($P < 0.05$).
[c]Saris et al. (2000).
[d]Mougios (2007).

Table III. Strength and performance of volleyball players (N = 25) before (T_0) and after (T_1) supplementation of Mg (experimental group) or placebo (control group).

Variable	Control group (n = 13) T_0	Control group (n = 13) T_1	P^a Intra	Experimental group (n = 12) T_0	Experimental group (n = 12) T_1	P^a Intra	P^b Inter
VO_2 max[c] ($mL \cdot kg^{-1} \cdot min^{-1}$)	49.3 ± 2.3	48.0 ± 3.0	0.060	48.7 ± 3.4	48.3 ± 4.7	0.691	0.490
Lactate ($mmol \cdot L^{-1}$)	12.9 ± 1.8	9.3 ± 1.8	0.000	13.4 ± 1.7	10.4 ± 2.1	0.001	0.524
Squat jump (cm)	36.6 ± 7.3	37.6 ± 2.9	0.528	37.4 ± 6.5	38.7 ± 4.3	0.179	0.853
Countermovement jump (cm)	38.7 ± 8.0	40.6 ± 4.2	0.264	40.0 ± 5.9	42.5 ± 5.4	0.002	0.702
Countermovement jump with arm swing (cm)	47.8 ± 5.9	48.5 ± 4.8	0.415	47.7 ± 6.7	50.7 ± 7.2	0.000	0.034

Notes: Data represent mean values ± standard deviations.
[a]Two-way repeated measures ANOVA with time ($T_0 \times T_1$) as within-participant factor were performed to establish the significances of intra-group differences ($P < 0.05$).
[b]Two-way repeated measures ANOVA with group (control × experimental groups) as between-participant factor were performed to establish the significances of inter-group differences ($P < 0.05$).
[c]Maximal oxygen uptake.

Table IV. Isokinetic parameters of knee muscle extensors of volleyball players (N = 25) before (T_0) and after (T_1) supplementation of Mg (experimental group) or placebo (control group).

Variable	Knee joint	Control group (n = 13) T_0	Control group (n = 13) T_1	P^a Intra	Experimental group (n = 12) T_0	Experimental group (n = 12) T_1	P^a Intra	P^b Inter
Peak torque (Nm)	Right	311.9 ± 56.2	301.1 ± 48.6	0.208	266.7 ± 43.1	266.2 ± 65.7	0.970	0.511
	Left	285.5 ± 41.9	291.7 ± 36.5	0.176	268.6 ± 41.8	264.7 ± 47.1	0.494	0.738
Potency (W)	Right	199.3 ± 38.8	199.85 ± 36.0	0.891	175.15 ± 31.9	174.4 ± 45.1	0.947	0.912
	Left	186.9 ± 33.5	190.9 ± 27.5	0.277	169.4 ± 32.0	180.4 ± 28.7	0.090	0.309
Total work (J)	Right	1278 ± 206.1	1237.4 ± 178.3	0.132	1125.8 ± 205.6	1098.1 ± 292.8	0.657	0.841
	Left	1217.1 ± 188.7	1239.4 ± 148.5	0.301	1125.9 ± 234.5	1175.7 ± 218.4	0.207	0.526

Notes: Data represent mean values ± standard deviations of variables determined at angular velocity of 1.05 rad · s^{-1}.
[a]Two-way repeated measures ANOVA with time ($T_0 \times T_1$) as within-participant factor were performed to establish the significances of intra-group differences ($P < 0.05$).
[b]Two-way repeated measures ANOVA with group (control × experimental groups) as between-participant factor were performed to establish the significances of inter-group differences ($P < 0.05$).

As shown in Tables IV and V, the extension peak torques of the right and left knee muscles of all players were greater than the flexion peak torques when assessed at the same angular velocity (1.05 rad · s^{-1}). In addition, the potency and total work parameters of the knee extensors (Table IV) were greater than those of the knee flexors (Table V). No significant differences were observed within or between the control and experimental groups regarding muscle extensor parameters at before and after supplementation. On the other hand, significant increases ($P < 0.05$) were observed within both groups in the performance of muscle flexors at before and after supplementation, but the differences between the groups were not significant.

Discussion

The concentration of Mg in the plasma is one of the key parameters employed in evaluating the nutritional status of the mineral. Plasma Mg is strongly correlated with the type of exercise, and its concentration typically increases with exhaustion after high-intensity exercises of short duration and diminishes with exhaustion after high-intensity exercises of long duration (Haralambie & Senser, 1980; Lares & Monteiro, 2006; Rayssiguier et al., 1990; Santos et al., 2011). In the present study, the levels of plasma Mg in the control and experimental groups of volleyball players were found to be lower at the end of the study period (after supplementation) than at the beginning (before supplementation), although all values were within the reference range. Interestingly, the reduction in plasma Mg was statistically significant in the experimental group, who had received Mg supplementation, but not in the control group. Since the decrease in plasma Mg occurred during the period of intense training, it is possible that the Mg pool was mobilised to the skeletal muscles.

The concentrations of erythrocyte Mg determined in the population of volley players were consistently above the minimum reference level. It would appear that the athletes were not Mg-deficient if the

Table V. Isokinetic parameters of knee muscle flexors of volleyball players (N = 25) before (T_0) and after (T_1) supplementation of Mg (experimental group) or placebo (control group).

Variable	Knee joint	Control group (n = 13) T_0	Control group (n = 13) T_1	P^a Intra	Experimental group (n = 12) T_0	Experimental group (n = 12) T_1	P^a Intra	P^b Inter
Peak torque (Nm)	Right	160.9 ± 20.5	179.2 ± 18.3	0.002	152.1 ± 33.6	168.6 ± 36.5	0.003	0.779
	Left	158.6 ± 16.3	173.1 ± 18.2	0.003	143.4 ± 27.9	156.5 ± 26.0	0.001	0.789
Potency (W)	Right	112.6 ± 19.2	127.3 ± 15.8	0.002	105.4 ± 26.1	117.9 ± 26.1	0.018	0.721
	Left	112.5 ± 15.1	120.0 ± 14.5	0.006	102.1 ± 22.0	112.4 ± 18.1	0.001	0.452
Total work (J)	Right	730.1 ± 119.2	801.9 ± 77.6	0.010	694.1 ± 174.4	749.8 ± 159.6	0.037	0.635
	Left	700.9 ± 184.5	784.0 ± 102.1	0.041	690.6 ± 156.6	738.2 ± 151.6	0.029	0.407

Notes: Data represent mean values ± standard deviations of variables determined at angular velocity of 1.05 rad · s^{-1}.
[a]Two-way repeated measures ANOVA with time ($T_0 \times T_1$) as within-participant factor were performed to establish the significances of intra-group differences ($P < 0.05$).
[b]Two-way repeated measures ANOVA with group (control × experimental groups) as between-participant factor were performed to establish the significances of inter-group differences ($P < 0.05$).

assumption that erythrocyte Mg level reflects the nutritional status of the individual is correct (Saris, Mervaala, Karppanen, Khawaja, & Lewenstam, 2000). Moreover, the level of erythrocyte Mg in the experimental group was not influenced by supplementation of the mineral during intensive training. Feillet-Coudray et al. (2002) reported that supplementation of Mg to healthy women over an 8-week period did not increase the concentration of erythrocyte Mg and explained this result on the basis of the adequacy of the Mg status of the population studied. It has been suggested that erythrocyte Mg levels reflect both acute and chronic changes in the Mg pool (Bohl & Volpe, 2002).

Regarding urinary Mg, the values determined in the population of volleyball players were within the normal range, and no significant differences were detected within or between the control and experimental groups at before and after supplementation. Although the concentrations of Mg in the plasma and erythrocytes indicated that the athletes were not deficient in the mineral, urinary Mg did not increase in the experimental group following supplementation, thus suggesting the absence of a surplus Mg pool.

A high vertical jump is one of the main attributes required by a volleyball player. Thissen-Milder and Mayhew (1990) consider that jumping ability is an important facet in the physical performance of volleyball players, since it is required in movements such as spiking and blocking as well as serving, passing, hitting and setting. The vertical jump demands considerable aerobic power and muscular endurance and is characterised by eccentric and concentric muscular action, particularly of the quadriceps muscles. Santos et al. (2011) reported that Mg intake was positively associated with the plyometric (squat jump, countermovement jump and countermovement jump with arm swing) and isokinetic (strength and power) performances of basketball, handball and volleyball players and emphasised the importance of Mg in muscle contraction and relaxation.

Results obtained in the present study revealed that the vertical jump performance of the experimental group increased either slightly (in the case of squat jump) or significantly (countermovement jump and countermovement jump with arm swing) at after supplementation period, thus confirming that Mg supplementation exerts a positive influence on this type of activity. This finding can be explained by the fact that Mg is a cofactor for creatine kinase, a key enzyme of anaerobic alactic metabolism, which is the main pathway required for volleyball athletes. Thus, the greater the supply of Mg, the more energy is produced for movements of short duration and high intensity such as vertical jumps. Cheng et al. (2010), following experiments with animal models, demonstrated that Mg supplementation reduced the levels of serum lactate and positively influenced performance during intense exercise. The enhanced performance may be explained by the extra energy available to the muscles to produce work (Cheng et al., 2010; Cinar et al., 2006; Nielsen & Lukaski, 2006).

Countermovement jump with arm swing is the most representative movement on court since the player has to use the lower and upper limbs concomitantly. While VO_2 max values were unchanged following Mg supplementation, peak exercise lactate levels were reduced significantly suggesting that the aerobic and lactic anaerobic metabolisms of the athletes were not affected by supplementary Mg. It is noteworthy, however, that alactic anaerobic metabolism is the predominant source of energy (80%) for the high intensity explosive movements associated with vertical jump. This metabolic system provides energy to the muscles by producing adenosine triphosphate from phosphocreatine and adenosine diphosphate, in a reversible reaction mediated by creatine kinase. Indeed, it has been reported that strenuous physical activity can give rise to an increase in plasma creatine kinase activity as a consequence of muscle catabolism (Uchida et al., 2009). In the present study, however, the activity of this enzyme was within the normal range at before and after supplementation period in both groups and was not influenced by Mg supplementation or intense exercise.

Isokinetic tests are very important for evaluating the fitness of athletes in general because they provide objective, reliable and reproducible information regarding muscle and joint function (Zakas, Mandroukas, Vamvakoudis, & Christoulas, 1995). Such tests allow the strength and power of different muscles on both sides of the body to be evaluated and can be used to detect possible imbalances between agonist and antagonist muscle activities (Perrin, Robertson, & Ray, 1987). Isokinetic values obtained at an angular velocity of 1.05 rad $\cdot$ s^{-1} are considered to provide the best representation of muscle function of volleyball players by virtue of the greater number of motor units recruited at the lower velocity (Siqueira, Pelegrini, Fontana, & Greve, 2002).

The peak torque values of the knee muscle extensors of the studied population of volleyball players were considerable larger than those of the knee muscle flexors, indicating that the strength and contraction efficiency of the knee extensors was high in comparison with the knee flexors. Lian, Engebretsen, Ovrebo and Bahr (1996) stated that more than 50% of the work produced in a vertical jump could be attributed to knee extensors, causing differential muscle demands that are capable of inducing adaptations in athletes.

In the present study, significant enhancements in knee muscle flexors, but not extensors, were observed in both groups of volleyball players at after supplementation period. However, such improvements were probably related to the intensive training programme and not to the supplementation of Mg since there were no significant differences between the groups regarding the development in isokinetic parameters. This finding contrasts with that of Setaro et al. (2008), who reported that the peak torque (at 1.05 rad $\cdot$ s^{-1}) of the knee muscle flexors of 9 volleyball players increased significantly after 4 weeks of supplementation with 500 mg of magnesium oxide. In this case, the peak torques of the right knee for the experimental and control groups were, respectively, 196 ± 19 and 170 ± 13 Nm ($P = 0.06$), while the peak torques of the left knee were 202 ± 19 and 76 ± 20 Nm, respectively ($P = 0.11$). In the present study, however, the control and treatment groups were not homogeneous with respect to strength and power of muscle extensors and flexors at before supplementation period, and this may explain why Mg supplementation did not appear to influence motor performance at after supplementation period.

Conclusion

Supplementation of Mg (in the form of MgO) at a dose rate of 350 mg $\cdot$ d^{-1} over a 4 week period improved alactic anaerobic metabolism in volleyball players as demonstrated by the increase (of up to 3 cm) in the plyometric parameters countermovement jump and countermovement jump with arm swing at after supplementation period. However, aerobic and lactic anaerobic metabolisms of the athletes were apparently not affected by Mg supplementation. Since the players were not Mg-deficient at before supplementation period, the enhancement in vertical jump performance following Mg supplementation was most likely related to the role of Mg as a cofactor for creatine kinase, the key enzyme of the alactic anaerobic energy system.

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