Original article

Effects of power training in mechanical stiffness of the lower limbs in soccer players

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A B S T R A C T

Objective: The aim of this study was evaluate whether leg stiffness (Kleg) changes after power training.
Methods: Forty professional soccer players were divided into 2 groups (20 were assigned to the trained group and 20 to the control group). A quasi-experimental study with pre–post intervention was conducted to estimate Kleg before (period 1) and after a six-week period of power training (period 2). Leg stiffness was measured using a three-dimensional filming method while soccer players ran on a treadmill at 13 km/h. The heights of squat jumps (SJ) and countermovement jumps (CMJ) were measured and the pre-stretch augmentation (PSA) was calculated before and after the training period in both groups.
Results: We found a significant increase in Kleg after the power training program. Significant positive linear relationships between Kleg and SJ height were found in both periods and groups, while CMJ height was not correlated with Kleg in the trained group during period 2. No significant relationships were found between Kleg and PSA in either case.
Conclusions: We concluded that Kleg can change significantly after a short power training program. Based on our results and previous studies, we suggest that these changes could be mainly associated with adaptions at muscle control level.

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Efectos del entrenamiento de potencia sobre la rigidez mecánica de miembros inferiores en jugadores de fútbol

R E S U M E N

Objetivo: El objetivo de este estudio fue evaluar si la rigidez de la pierna (Kleg) cambia después de un período de entrenamiento de potencia.
Métodos: Cuarenta jugadores profesionales de fútbol se dividieron en 2 grupos (20 se asignaron al grupo entrenado y 20 al grupo control). Se realizó un estudio cuasi-experimental con pre-post intervención para estimar Kleg antes (periodo 1) y después de 6 semanas de entrenamiento de potencia (período 2). Se cuantificó Kleg mediante la reconstrucción de imágenes en 3 dimensiones mientras los sujetos corrían en una cinta a 13 km/h. Se midieron las alturas de squat jumps (SJ) y countermovment jumps (CMJ) y se calculó el pre-stretch augmentation (PSA) antes y después del período de entrenamiento para ambos grupos.
Resultados: Se encontró un aumento significativo en Kleg después del programa de entrenamiento. Se encontraron correlaciones lineales positivas entre Kleg y la altura de los SJ en ambos períodos para los 2 grupos, mientras que la altura CMJ no se correlacionó con Kleg únicamente en el grupo entrenado durante el periodo 2. No se encontraron relaciones significativas entre Kleg y PSA.

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Conclusiones: Llegamos a la conclusión de que *Kleg* puede cambiar significativamente como producto del entrenamiento de potencia. Basados en nuestros resultados y considerando estudios previos sugerimos que estos cambios podrían estar asociados principalmente con adaptaciones a nivel del control muscular.

Efeitos do treinamento de potência sobre rigidez mecânica dos membros inferiores em atletas de futebol

R E S U M O

Objetivo: O objetivo deste estudo foi avaliar mudanças na rigidez da perna (Kleg) após um período de treinamento de potência.

Método: Quarenta jogadores de futebol profissionais foram divididos em 2 grupos (foram designados 20 ao grupo treinado e 20 ao grupo controle). Se realizou um estudo quase experimental com uma intervenção pré/pós teste para estimar a Kleg antes (período 1) e após 6 semanas de treinamento de potência (período 2). A Kleg foi quantificada através de um método de filmagem tridimensional enquanto os sujeitos corriam em uma esteira a 13 km/h. Foram medidas as alturas nos testes *squat jumps* (SJ) e *countermovment jumps* (CMJ), e foi medido e calculado o *aumento pré-estiramento* (PSA), antes e depois do período de treinamento para ambos os grupos.

Resultados: Foi encontrado um aumento significativo em Kleg após o programa de treinamento. Foi encontrado uma correlação linear positiva entre a Kleg e a altura do SJ em ambos os períodos para os dois grupos, enquanto a altura do CMJ somente não se correlacionou com a Kleg no grupo treinado durante o período 2. Não foram encontradas relações significativas entre a Kleg e o PSA.

Conclusão: Chegamos à conclusão que a Kleg pode mudar significativamente como resultado ao treinamento de potencia de curta duração. Com base em nossos resultados e considerando estudos anteriores, sugerimos que estas alterações podem estar associadas, principalmente, com adaptações a nível de controle muscular.

Introduction

When people run, the musculoskeletal structure of the lower limbs can be modelled as a spring–mass system consisting of a linear spring which represents the stance limb, and a point mass equivalent to the body mass.[1–3] With this assumption, the spring stiffness would represent the overall mechanical stiffness of lower limbs during the stance phase.[1,3–5] Mechanical stiffness of lower limbs has been evaluated through different experimental approaches, but Kleg is one of the most used ones.[6] This is a global parameter that represents the stiffness of the muscle-tendon units in the legs during the effective ground contact phase.[4,6]

Kleg is an important variable that can influence the performance of athletes.[6,7] Furthermore, it has been established that power training programs could generate important changes in the structural and mechanical properties of the locomotor system, enabling changes in strength and speed rates.[8] Considering that the rate of force development and sprint kinematics are included among the athletic variables that have been associated with Kleg,[6] the evaluation of possible changes in Kleg after power training could be of great interest to the sport community. Specifically in sports like soccer, in which performances include high intensity intermittent activities,[9] explosive strength or power is one of the most important capacities to work in physical training.

Regarding the factors that determine Kleg, Hobara et al.[8] suggested that this variable is partly dependent on the muscle activation pattern and probably in short-latency stretch reflex response of the triceps surae. In a subsequent study, Hobara et al.[10] found that Kleg of power-trained athletes is significantly higher than Kleg of distance runners. Furthermore, cross-sectional studies indicate that physical power training enhances Kleg.[11,12] However, optimal Kleg required for running remains a topic of debate[6,13–15] and few studies are available that discuss the effect of power training on Kleg levels during human running.

Based on the literature that has been considered so far, a better understanding of changes in Kleg after a power training program contributes to the development of more effective training methods in soccer.

The goal of this study is to evaluate if Kleg changes after a short power training program. We hypothesized that after this training program an increase in the value of Kleg would be observed. Moreover, through the relationship between Kleg, SJ and CMJ heights, performed to evaluate the training program, and considering results of previous studies, we suggest possible explanations for Kleg values found before and after the training period.

Methods

Sample

Forty professional soccer players (24.7 ± 3.1 years, 73.3 ± 2.5 kg), without any recent injury, voluntarily participated in this study. They were selected by convenience (we worked with a full professional team) and divided randomly into two groups. One group underwent power training (group 1) and the other was the control group (group 2). The sample size in each group was estimated by the model for comparison of two means:

$$n = \frac{2(Z_\alpha + Z_\beta)^2 \times S^2}{d^2}$$

where n is the number of subjects in each sample, Z_α and Z_β are the values corresponding to desired risk, S^2 is the variance of Kleg in the control group (taken from the literature[6]), and d is the minimum difference value to be detected (taken from literature).[6]

All the participants were informed about the objectives and the characteristics of the study, and their consent was obtained. This study was carried out according to the requirements of the local Committee for Medical Research Ethics and current Uruguayan laws and regulations.

Experimental design

A quasi-experimental study with pre–post intervention was conducted to estimate Kleg. The procedure included 2 test sessions before (period 1) and after a training period of six weeks (period 2). The training program focused on enhancing the capacity of the soccer players to apply and develop maximum strength in the shortest period of time (power training). During the power training period, athletes from both groups received the same additional soccer training sessions. This was an unavoidable factor of adaptive and functional interference.

The six-week training period was selected based on previous studies of power training.[16] The total duration was divided into two mesocycles of 3 weeks each. The load dynamics for each mesocycle was 2-1, this means two microcycles in which the load was increasing and one microcycle in which the load was decreasing. Each microcycle consisted of three training sessions, and the workload was distributed following the same dynamics expressed for mesocycles (2-1).[16]

In the training sessions, jumps normally used in power training were performed. These included coordinative variants (multi-jumps), vertical jumps and horizontal jumps.[16] The performance of the training plan is showed in Table 1.

To evaluate the training plan, hopping tests were performed in periods 1 and 2. The training was evaluated through the SJ and CMJ heights.[17] Five jumps of each type were analyzed in each individual in each period. In addition, the pre-stretch augmentation (PSA) was calculated as follows:[17]

$$PSA(\%) = (CMJ - SJ) \cdot 100SJ^{-1}$$

To calculate Kleg, each subject ran on a treadmill for 10 min at 13 km/h in period 1 and period 2. The running speed selected for the study is associated with the step frequency of 2.5 Hz, which corresponds to the middle range of frequencies selected in previous studies to evaluate hopping and jumping, in which the lower limbs behaved like a simple spring–mass system.[11,18,19]

During the running and jumping kinematics test, data were collected using a VICON MOTION SYSTEMS (*Oxford Metrics Ltd.*) operating with 8 synchronized digital video cameras at 200 Hz. Infrared light-emitting diodes were placed in 40 anatomical references. A three-dimensional reconstruction was performed to determine the position of athlete's centre of mass (CM) during the stance.

Kleg evaluation

The coordinates of the CM for support during the races were exported to calculate Kleg in Matlab R2007b® (*Mathworks, Inc.*). Kleg was determined as the ratio of the maximum ground reaction force during contact (F_{max}) times the maximum leg spring compression displacement at the instant that this compression is maximal (VCL), where the compression of the leg spring is actually the vertical displacement of CM after landing[6,7]:

$$Kleg = F_{max} \cdot VCL^{-1}$$

Considering that force platforms records limit the number of cycles to study and hinder the control of speed, in this study we opted for determining Kleg from kinematic data rather than from force plate analysis. The values of Kleg (in kN m^{-1}) were calculated

Table 1
Training program. Volume distribution for each Meso and Microcycles.

Meso-cycle	I			II		
Micro-cycle	1	2	3	1	2	3
Type of exercise: Jumps						
1 – Coordinative variants	300	450	400	450	600	500
2 – Vertical jumps	150	230	200	230	300	250
3 – Horizontal jumps	50	70	60	70	100	80
Total volume	500	750	660	750	1000	830
Main muscular action						
1 – Coordinative variants						
SSC	300	450	400	450	600	500
2 – Vertical jumps						
Concentric	90	130	100	100	120	50
Eccentric – Isometric	0	0	0	0	0	0
SSC	60	100	100	130	180	200
3 – Coordinative variants						
SSC	50	70	60	70	100	80
Angular variations						
1 – Coordinative variants						
Minimal (average)	300	450	400	450	600	500
2 – Vertical jumps						
Concentric phase						
1/4 Flexion	20	40	30	40	70	50
1/2 Flexion	70	90	70	60	50	0
Full flexion	0	0	0	0	0	0
Vertical jumps						
During SSC						
Minimal flexion (short SSC)	20	30	30	50	80	100
1/2 Flexion (long SSC)	40	70	70	80	100	100
3- Horizontal jumps						
Minimal Flexion	50	70	60	70	100	80

SSC, stretch-shortening-cycle. Data are expressed in number of repetitions.

Table 2
Heights achieved in SJ and CMJ and PSA and Kleg values of control and trained groups evaluated in both periods (mean±standard deviation).

	Period 1		Period 2	
	Group 1	Group 2	Group 1	Group 2
SJ (cm)	38.6 ± 2.5[*]	38.5 ± 2.2[*]	39.1 ± 1.0[*]	43.6 ± 0.7[*]
CMJ (cm)	41.3 ± 2.0[*]	41.4 ± 2.5[*]	41.5 ± 2.1[*]	44.4 ± 1.7
PSA (%)	7.1 ± 2.8	8.0 ± 3.6	6.6 ± 2.5	1.9 ± 2.2
Kleg (kN m^{-1})	21.7 ± 0.4	21.5 ± 0.3	21.9 ± 0.3	25.9 ± 0.4

SJ, squat jump; CMJ, countermovement jump; PSA, pre-stretch augmentation; Kleg, leg stiffness.

[*] Significant correlations between the jump analysis and Kleg value for each group in each period. Differences found between groups for one period, and between periods for one group are detailed in the text.

through the method proposed by Morin et al.[20] for measuring stiffness during running only from body mass, contact time (t_c) and flight time (t_f) values, so that F_{max} is given by:

$$F_{max} = m \cdot g \cdot \frac{\pi}{2} \cdot \left(\frac{t_f}{t_c + 1} \right)$$

where m is the athlete's body mass (in kg), g is the gravitational acceleration and t_c and t_f, are flight and contact times (in s), respectively.

Statistical analysis

All the statistical analysis was performed in SPSS for Windows software (version 11.0.1J SPSS Inc.). Data distribution was first checked using the Shapiro–Wilk normality test. Since all the data were normally distributed, paired sample *t*-tests were performed to compare the heights reached in SJ and CMJ, and PSA, between different periods for both groups, and between different groups in the same period, to test whether training caused significant effects. The same analysis was carried out to compare Kleg to test a potential effect of the training program on mechanical stiffness. Furthermore, we used Pearson correlation coefficient to examine the relation between Kleg and SJ, CMJ and PSA before and after the training program, separately for each group. In all the tests, the significance level was set at $p < 0.05$. Unless otherwise specified, data are expressed as mean ± SD.

Results

Values obtained in this study for each group and periods are shown in Table 2. SJ and CMJ heights, as well as PSA calculation during period 1 showed no significant differences between the control and trained group. Significant differences were observed during period 2 when comparing the height achieved in SJ ($p = 0.017$) and the PSA ($p = 0.04$) between groups. Although the height achieved in CMJ during period 2 was, in average, 3 cm higher in the trained group, no significant differences could be established. The comparison of each group in different periods showed there were no significant changes in SJ, CMJ and PSA results in the control group, while the trained group showed a significant increase in the height achieved in SJ ($p = 0.013$) and a significant decrease in PSA ($p = 0.04$). In average, heights achieved in CMJ by the trained group increased approximately 3 cm compared to period 1, but no significant differences could be established.

Regarding the Kleg values, similar results were obtained for both groups in period 1. No significant changes were found in Kleg values in the control group when comparing period 1 and 2. The trained group showed a significant increase in Kleg ($p = 0.001$) in period 2 with respect to period 1. This increase caused significant differences in Kleg ($p = 0.003$) when comparing the trained group against the untrained group in period 2. As indicated in Table 2, a significant

positive linear relationship ($p < 0.05$) could be established between Kleg and SJ height in each one of the analyzed periods for both groups. While the CMJ heights were also correlated to Kleg before the training period for both groups, this association was only maintained for the control group in period 2. No significant correlations were found between Kleg and PSA in any case.

Discussion

In this paper we analyzed whether Kleg changed after a short duration power training program. We hypothesized that, after this training program, an increase in the value of Kleg would be observed.

The first consideration that we had to make was that, during the power training period, athletes from both groups received additional soccer training sessions. This was a factor that could involve adaptive and functional interference, which we could not avoid. However, the additional soccer training sessions performed by the athletes from both groups during the training period were similar, since they were part of the same team.

Regarding the effectiveness of the training regime, we consider it is reflected in the significant differences in the SJ heights achieved ($p = 0.017$) and in PSA ($p = 0.04$) when the trained group was compared to the untrained group, in the second period. The difference in the height achieved in the CMJ by the trained group when compared to the control group was three centimetres. Even though it was not significant, it could also be considered as a reflection of the effectiveness of the training process. The height reached in the SJ is independent from the accumulated elastic energy and reflexes, while the height of CMJ is influenced by these factors.[21] Therefore, the changes observed in the heights of the jumps and PSA values suggests that this is dependent on the degree of muscle activation.

Some authors, like Hobara et al.,[10] suggested that Kleg is partly dependent on the muscle activation pattern (coordination). Due to this, the changes observed in the heights of the jumps analyzed by comparing groups and periods, should be consistent with the values found for Kleg (Table 2).

Few studies have assessed stiffness at lower running speed, as has been done in this study (13 km/h). We selected that speed because it is close to the ones used in real situations and the assumptions for the model used to calculate Kleg are perfectly fulfilled.[14,15]

To estimate Kleg, we used the method proposed by Morin et al.[20] but, unlike these authors, who used force platforms for data input that allow calculation of F_{max}, we estimated F_{max} from image data. The error in measuring F_{max} directly from a force platform will obviously be less than estimating it from spatiotemporal data. However, as in a previous study, we determined the intraclass correlation coefficient (ICC) from the force recordings and kinematic estimates and found an ICC of 0.89. We believe it is appropriate to compare our results with studies in which platforms were used. In fact, Kleg values obtained in this study were similar to those obtained in a recent study made by Gaudino et al.[22] In that study, the race of soccer players was analyzed and Kleg was calculated through the same method that we used here, but F_{max} was measured with force platforms. The mean values found in this study for Kleg ranged from $21.5 ± 0.3$ to $25.9 ± 0.4$ kN m^{-1}. The minimum value of this range is very similar to the average value found for Ktot in natural grass ($20.77 ± 3.82$).[22] These authors refer to Ktot instead of Kleg, because stiffness is the ability of the system to withstand a strain, and it obviously varies according to the surface that the person is in contact with.[14] As the natural grass is certainly more rigid than other surfaces analyzed by Gaudino et al.,[23] the vertical displacement of CM on that surface is expected to be closer to a one-leg spring model.

The Kleg values we determined are comparable to those reported in the literature, experimentally obtained by using a different procedure as is the case of Hobara et al.,[8] who used a force platform and evaluated Kleg at a hopping frequency of 2–2.4 Hz. This supports the validation and the reliability of the adopted theoretical method used in this work, even considering that our Kleg values are influenced by the degree of deformation of the treadmill during each step. In any case, the most important aspect of our study is the change in Kleg values, so that possible errors when calculating this parameter do not imply any limitation to the purposes of our investigation.

The significant increase in Kleg values observed after six weeks of power training (25.9 ± 0.4 kN m^{-1} trained group in period 2) could be associated with changes in the muscle-tendon units which participate in the running process.[8,10] During the run, these units are exposed to stretching and shortening dependently on the stiffness of their components, which in a simplistic analysis, could be divided into tendons and muscle fibres. Variations in the relative motion of the tendon and muscle fibre structures could be a possible explanation for the observed increase in stiffness, and can lead to an increase in joint stiffness, also altering the VCL.[10] Training produced morphological changes in both, structural fibres, and tendons. On the other hand, studies in humans and in animal models, suggest that training can lead to change in muscle activity.[24] These two changes can generate an increase in the stiffness of each one of the different components of the muscle-tendon units, causing an increase in joint stiffness and hence in Kleg. The deformation of each one of these components depends on their relative stiffness and, in the case of muscle fibres, is closely associated to the degree of activation.[24,25] In fact, a previous study suggests that there is a neuromuscular strategy to control Kleg.[7] At low speeds, such as those studied here, muscular activation is low to moderate and thus the imposed stretching of muscle-tendon units involved in movements can be more easily associated with significant deformations of muscle fibres than that of tendons. In this way, small changes in the degree of activation could significantly influence Kleg values. Although we did not perform an electromyographic analysis of the muscles involved, it is well known that a power training program seeking to increase explosive force levels can lead to changes in active muscle participation. This was concluded in Hobara,[11] where Kleg control at a preferred frequency during hopping was analyzed. In this study, power training was evaluated through vertical jumps. As already discussed, we found a significant increase in SJ performance in the trained group when comparing period 2 (after training) with period 1 (before training), though there was no significant change in CMJ. Furthermore, only SJ height remained correlated to Kleg in the trained group before and after training, and it increased slightly. Explosive strength without pre-stretching depends primarily on the ability of muscle contractile components to generate a substantial force, which is determined by the ability to achieve high recruitment, synchronization and initial codification rates of rapid motor units.[25]

Therefore, the changes found in Kleg and SJ heights, the results of the analysis of CMJ and PSA and the Kleg correlations with other variables suggest that changes are mainly associated with variations in muscle control. In this way, our results are consistent with the idea raised in Komi,[21] that initial adaptations during a power training are of neuro-coordinative nature.

For future studies, it would be interesting to perform such analysis including records of muscle activity. Different periods of power training should also be evaluated to analyze whether changes in the training extension imply major changes in Kleg and thus determine the optimum training period to develop Kleg. This would be of great interest among the sport and research communities considering the close relationship between mechanical stiffness and athletic performance.

Conflicts of interest

The authors have no conflicts of interest to declare.

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