J Musculoskelet Neuronal Interact 2020; 20(4):488-497

Journal of Musculoskeletal and Neuronal Interactions

Original Article

Effect of Training and Match Loads on Hamstring Passive Stiffness in Professional Soccer Players

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Abstract

Objective: the purpose of this study was to identify differences in hamstring passive stiffness between the pre-season and in-season periods. **Methods**: Hamstring strength and passive stiffness were measured in professional male soccer players before and after the pre-season (4 weeks), and after the in-season (6 weeks) periods using an isokinetic dynamometer. Muscle passive stiffness was determined from the slope of the passive torque–angle relationship. External loads (acceleration and jumps) were monitored by GPS and internal loads by questionnaire. **Results**: Hamstring passive stiffness increased after 10 weeks of training and matches, without changes in passive peak torque and range of motion. The hamstring passive stiffness modifications were associated with the volume and intensity of accelerations and jumps. The individual data analysis also provided some support for the suppression of the biomechanical adaptation in the subjects with relatively large external load. **Conclusions**: Regular training and match workouts increase hamstring passive stiffness in professional soccer players but the adaptation of muscle-tendon unit passive elements might not occur if players experience excessive mechanical stress.

Keywords: Adaptation Effect, Jump, Running, Serial Elastic, Strength

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Introduction

The results of the Union of European Football Associations UEFA Elite Club Injury Study revealed that 70% of hamstring injuries occurred during sprinting or high-speed running[1]. External factors, such as training load, which is defined as the physical work prescribed in the training plan (the sum of soccer training and fitness training)[2], match frequency[3], and accumulated weekly high-intensity running load[4] were associated with an increased likelihood of hamstring injuries. The training load stresses various physiological sub-systems as well as generating mechanical stresses on musculoskeletal tissues. However, biomechanical adaptation may be slower than physiological adaptation leading to the overloading of the musculoskeletal system capacity and increased risk of injury[5].

It was previously reported that a disproportionately high number of overuse injuries occur during the pre-season compared with the in-season period[6,7] and at the end of the competitive season[8]. The reasons proposed to explain this observation were the sudden increase in training volume and intensity[6], week-to-week large fluctuations in training load[9] or large decrease in training workloads during the competitive period[10]. Biomechanical adaptation takes place through mechanical stresses to the musculoskeletal tissues changing their mechanical properties[11] and previous reports have shown that impaired adaptation of musculotendinous stiffness has been related to a higher rate of non-contact soft tissue injuries in professional athletes[12,13].

Connective-tissue components surrounding whole muscles, fascicles, and muscle fibers provide the framework that combines the contractile elements into a functional unit and affects the mechanical behavior of the whole muscle.

The authors have no conflict of interest.

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Edited by: G. Lyritis
Accepted 24 March 2020

The connective tissue matrix observed in the fiber bundles increases passive muscle stiffness[14]. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures[15]. Decrease stiffness of the muscle's extracellular matrix or tendon reduces the absorption of mechanical energy in the elastic component of the muscle–tendon unit during active lengthening. This can increase the amount of muscle fiber (contractile element) strain and influence the magnitude of muscle damage or muscle-tendon unit strain injury[16,17].

Previous studies showed that tendon stiffness adaptation is the time-course of training and requires 8–12 weeks of intervention[18–20]. Nordic hamstring eccentric strength training for 6 weeks increased muscle volume and physiological cross-sectional area, but did not have an effect on muscle fascicle length and stiffness or eccentric hamstring strength[21]. However, a 6-week stretching program significantly increased the knee extension ROM and hamstring passive stiffness in the new ROM[22].

The complexity of the causes of hamstring injuries requires a knowledge of the relationship between training loads, hamstring strength (physiological adaptation) and changes of mechanical properties (biomechanical adaptation) of the muscle. Monitoring training load and together with changes of hamstring strength and passive stiffness could help define the optimal load which balances maximum training effect with minimum (or acceptable) injury risk[23].

The purpose of this study was to identify differences in passive stiffness of hamstrings between the pre-season and in-season periods in professional soccer players. We hypothesized that the changes in passive stiffness of hamstrings are related to training duration, external load types and intensities. Using the Global Positioning Systems (GPS) to measure acceleration and deceleration events or jumps[5] will allow us to associate training loads with biomechanical adaptations of the muscle tissues and to test the proposed hypothesis.

Materials and methods

Participants

Eleven football players, selected for the club's main team competing in the national 1st division, were involved in the study: 2 center-backs; 2 full-backs; 4 midfielders; 2 wingers and 1 forward. Players were included if they were healthy and regularly active for the last 6 months. Exclusion criteria were hamstring injuries during the last 6 months, ACL rupture and ACL reconstruction within 1 year after trauma, knee or back pain, postural abnormalities. Their mean age, height, body mass, and body fat were 23.8±1.7 years, 181±10 cm, 76.1±6.5 kg, and 9.0±3.2%, respectively. All participants completed the same training/playing schedule. During the in-season period 9 of 11 players had transient complaints related to health, muscle or joint pain but their training attendance was above 90%. Six players participating in all, and for at least 70% of the duration of matches, while other players participated in at least 6 matches with not less than 50% and not more than 66% competition time.

Each participant read and signed a written informed consent form consistent with the principles outlined in the Declaration of Helsinki. The local Biomedical Research Ethics Committee approved this study.

Training program

The pre-season period lasted 30 days, including 3 rest days with no training. The players trained once a day for an average of 16 days; they completed two workouts per day for 4 days and played on average eight games per pre-season. Twelve of the training days were devoted to specific conditioning and endurance training (53%±28% of workout time), and technical skill development (45%±28% of workout time). Nine of the training days were devoted to specific conditioning and endurance training (26%±9% of workout time) and technical (34%±18% of workout time) and tactical (40%±17% of workout time) skill development. Gym workout was included during the 12 workout days. Flexibility training was not included in the regular training program. However, brief dynamic stretching was used for warm-ups before training sessions and competitions.

The in-season period lasted 40 days, of which 6 days were for resting. During this period, the players participated in six games. Seven of the training days were devoted to specific conditioning and endurance training (56%±11% of workout time) and technical skill development (44%±11% of workout time). Twenty-one of the training days were devoted to specific conditioning and endurance training (33%±17% of workout time) and technical (29%±13% of workout time) and tactical (38%±21% of workout time) skill development. Gym workout and flexibility training were not included in the training program.

Study design

This study used an observational research design. Hamstring strength and passive stiffness were measured before the season (baseline), after the pre-season (4 weeks), and 6 weeks after the in-season started. Before each testing session, the subjects completed an 8 min warm-up at a cycle ergometer at 50 W. After this warm-up protocol, three passive maximum knee extensions were performed to measure ROM and passive resistive torque using an isokinetic dynamometer (Figure 1). After the passive knee extension and familiarization with the strength test procedure, the players were tested over three repetitions of concentric knee flexion, concentric knee extension, and eccentric knee flexion at 60°/s and 180°/s. Finally, players performed two maximum isometric contractions of the knee flexors. All measurements were performed on the participants' dominant leg by the same investigators at the same time of day between 8.00 and 13.00. Neither of the participants had complains about any pain in the legs on the testing days. They were tutored to maintain their normal diet on testing days and abstain from

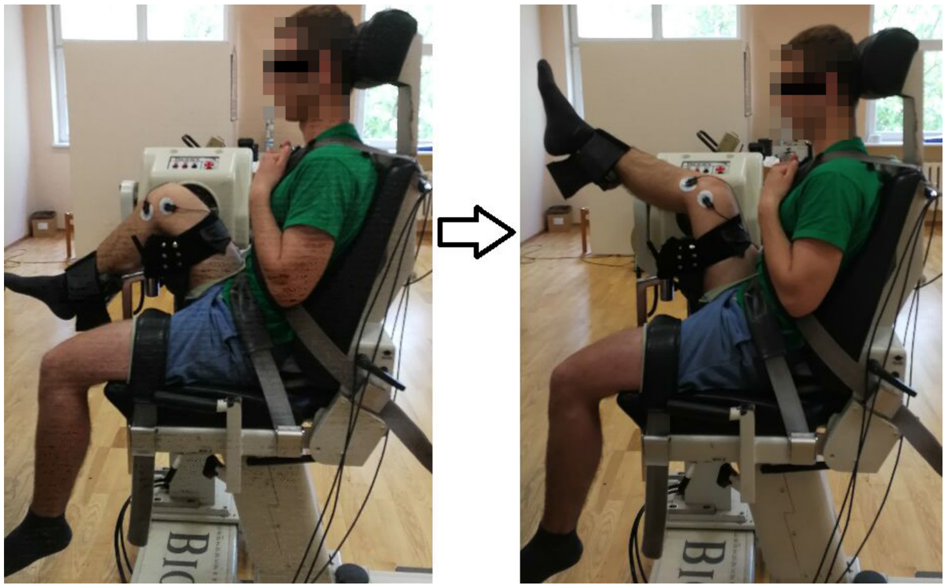

Figure 1. Position for passive knee extension testing and stretching maneuver on Biodex system 3. On the left side of the picture shows the starting position with the knee at 80° and the hip in approximately 120° flexion. On the right side - the position at the end of stretching - point of maximum knee extension without pain.

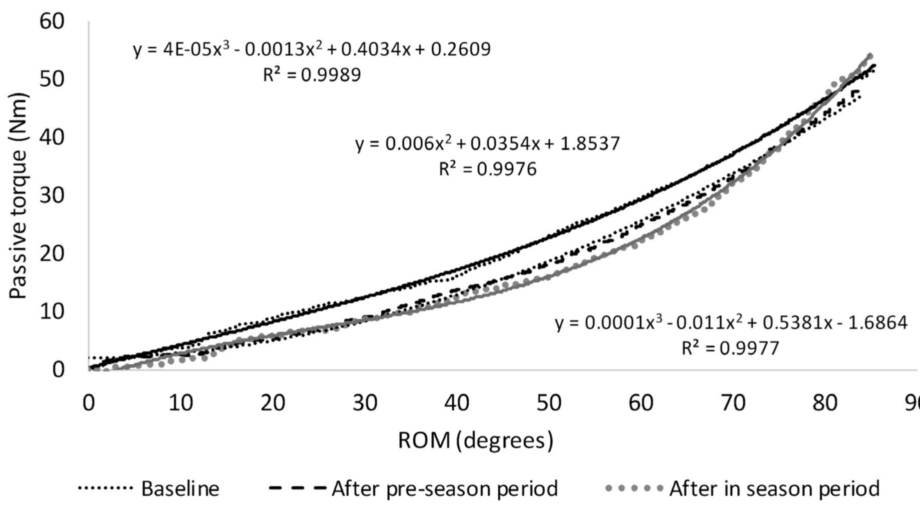

Figure 2. The passive torque–angle relationship fitted to the third-degree polynomial before season (baseline), after the pre-season and after the in-season period for the same soccer player.

consuming any drugs or caffeine. The temperature in the laboratory was kept stable between 20°C and 22°C.

Passive resistive torque, ROM, and muscle passive stiffness

The participants were seated on a Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Inc., Shipley, NY, USA) with no shoes, hip flexion of approximately 120° and the knee at 80° (shank placed at 50° below the horizontal; fully extended knee is at 180°; Figure 1). The pelvis and both thighs were stabilized with Velcro straps. The axis of rotation was fixed at the knee joint and the lever arm pad was attached proximal to the malleolus. In this position, the dynamometer passively extended the knee at the angular velocity of 5°/s to the point until the participant verbally reported unpleasant sensation. Passive torque and knee angle were recorded for further analysis. The procedure was repeated three times with 1 min rest after each passive knee extension.

The passive torque–angle relationship was fitted to a second or third-degree polynomial using a least squares method allowed the calculation of hamstring stiffness as the increase in passive torque between 90%–100% of maximum ROM (Figure 2). Normalization of the hamstring passive stiffness was performed by dividing the stiffness indices by the passive peak torque of each participant. Measurements were only accepted if knee flexor muscle activity was less than 5% of EMG max, which was determined during the maximum isometric strength test as the mean peak of a root mean squared (RMS) activity. Three passive maximum knee extension ROM, peak passive torque, and muscle passive stiffness measures were averaged for further analysis.

Electromyography and signal processing

Before the warm-up, the surface EMG signals were recorded with preamplified electrodes (EL254S; BIOPAC Systems, Santa Barbara, CA, USA; with a 30 mm interelectrode distance) attached to the shaved and cleaned skin of the right upper third of the biceps femoris muscle with a ground electrode fixed over the medial and lateral side of the patella. EMG signals were filtered with a band pass of 10–500 Hz using a fourth-order Butterworth filter; otherwise, a Butterworth second-order low-pass filter of 10 Hz was applied for torque and ROM signals. The EMG amplitude was transformed into an RMS for further calculations. Data were sampled at 1000 Hz and recording was synchronized with those of torque and angle during the stretching procedure described above.

Concentric and eccentric voluntary torque

Isokinetic peak concentric torque of knee extensors, and peak concentric and eccentric torque of knee flexors was measured using the Biodex System 3 device in a seated position. Three maximal voluntary concentric knee extensions and flexions and three maximal voluntary eccentric knee flexions were performed at 60°/s and 180°/s 24 with ROM of 90°; i.e., from 80° to 170° (180° = full knee extension). Peak value of three trials was used for further analysis. The 10 s of rest was set between each action and 60 s of rest between series of voluntary torque measurements at different velocities. Participants were instructed to perform push/pull as "fast and hard" as possible at the start of the lever arm movement, from a completely relaxed state, and to keep efforts for the entire ROM. For each contraction, torque, angle, and angular velocity signals were recorded at a sampling rate of 100 Hz. The isokinetic dynamometer used an automated gravity correction.

External load

Global Positioning System (GPS) OptimEye S5 (Catapult Sports) was used for monitoring players external load (EL) as the biomechanical component of workouts based on acceleration measurements during training and matchers. The OptimEye S5 apparatus contains a built-in +/-16*G* triaxial accelerometer, 200–2000 deg/s triaxial gyroscope, and a triaxial magnetometer, which samples at a frequency of 100 Hz. The unit was located between the scapula in a custom-made vest (Catapult Sports) worn under the player's match jersey. The same subject used the same device during all testing. The data collection was monitored in real time using the manufacturer software Catapult Sprint (version 5.1.4, Catapult Sports, 2014). EL was calculated using the accelerometer data. It was expressed as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (X, Y and Z axis) and divided by 100. Data was expressed in arbitrary units (A.U.)[25]. Then "Inertial Movement Analysis" (IMA) function was applied to extract acceleration, deceleration and jumps events classified by intensity: low (1–2 m/s^2), moderate (2–3 m/s^2), high (>3 m/s^2), and total (>1 m/s^2)[26]. According to 27 acceleration event intensity may be interpreted as: an action with an acceleration of >3 m/s^2 from standing and trotting, between 2 and 3 m/s^2 from jogging, and between 1 and 2 m/s^2 from running. Jump events were counted and sorted by period based on an intensity rating of low (0–20 cm), moderate (21–40 cm), and high (≥41 cm)[28]. The total value of jump events for each participant was calculated as the sum of all jumps at the different intensities.

Internal load

The subjective Rating of Perceived Exertion (RPE) was used to express internal psychophysiological load. The RPE is a way of monitoring the training load perception taking into consideration both intensity and the duration of a training session. Players were instructed to rate the global intensity of all sessions and matches using a modified category ratio scale going from 0 to 10[29]. All players were familiar with the RPE scale and had previous experience rating the perceived exertion of training drills and small-sided games. The session RPE score representing the magnitude of global internal load (IL) was calculated by the multiplication of Rating of Perceived Exertion and the length of training (mins) and expresed in Arbitrary Units (A.U.)[30].

Statistical analysis

Descriptive data are presented as the mean ± standard deviation (SD). One-way ANOVA for repeated measures as a time (baseline, after pre-season, and after the in-season period) factor was used to determine the effects of the loads on dependent variables (active and passive peak torque, ROM and passive stiffness). One-way ANOVA for repeated measures as a time (week I, week II, week III and week IV) factor was used to determine changes of EL and

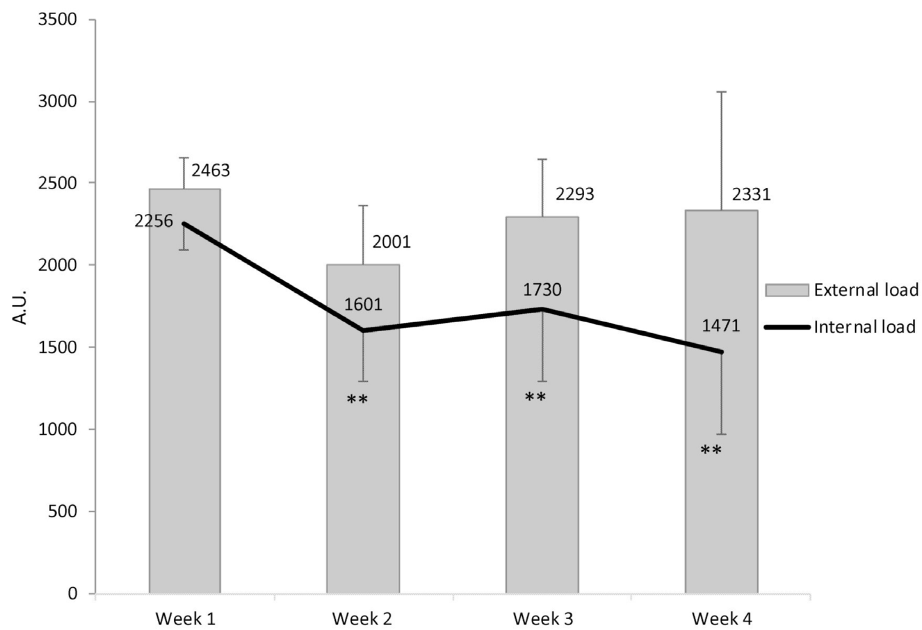

Figure 3. External and internal player load per week in-season period. **, significantly different (P < 0.01) compared with the Week 1 value.

Table I. Average acceleration, deceleration, and jump events at different intensities during the in-season period including training sessions and matches. Values are means ± SD.

Load	Intensities			Total
	Low	Moderate	High	
Acceleration	1027.41 ± 261.40	355.12 ± 89.94	220.65 ± 49.73	1603 ± 102.52
Deceleration	1394.21 ± 378.15	498.81 ± 145.79	256.08 ± 85.11	2108 ± 592.04
Jumps	158.22 ± 97.64	146.66 ± 61.51	53.44 ± 26.29	363 ± 150.93

RPE during the in-season period. ANOVAs were followed by Bonferroni correction for pairwise comparisons of main effects. The partial eta squared (η^2) was presented to estimate the effect size for one-way repeated-measures ANOVA. A criterion alpha level of $P<0.05$ was used to define statistical significance. Linear regression analysis was performed to assess the relationships between the changes in hamstring passive stiffness and EL types and intensities during the in-season period. A confidence interval (95%) for the correlation coefficient was obtained using Fisher's z transformation. Statistical analyses were performed using the IBM SPSS Statistics software (v. 22; IBM Corporation, Armonk, NY, USA).

Results

The mean value of the EL accumulated during the last four weeks in-season period was 9088.87±973.40 A.U. The average IL was significantly lower 7057.59±795.25 A.U. ($p<0.001$). Changes of EL and RPE per week are presented in Figure 3. Repeated-measures ANOVA showed a significant impact of training weeks on RPE ($F=9.53$, $P<0.001$, η^2= 0.488). During the three last weeks of in-season period, RPE was significantly decreased ($P<0.01$) while the EL of each week did not differ.

The average acceleration, deceleration, and jump events at different intensities performed during the last four weeks in-season period are presented in Table I. Accelerations contributed 9.88±1.79 % of the external player load, whereas decelerations contributed 13.14±2.31 % and jumps only 2.18±0.76 %. 64.16±4.23 % of the all accelerations events were performed at low intensity, 21.93±1.49 % at moderate intensity and 13.92±3.20 % at high intensity. Deceleration events were distributed as follow: low intensity 65.21±3.94 %, moderate intensity 22.89±1.51 % and high intensity 11.90±2.72 %. Low, moderate and high jumps contributed 42.87±11.87 %, 42.46 ± 8,97 % and 14.91±6.45 % of the all the jumps performed, respectively.

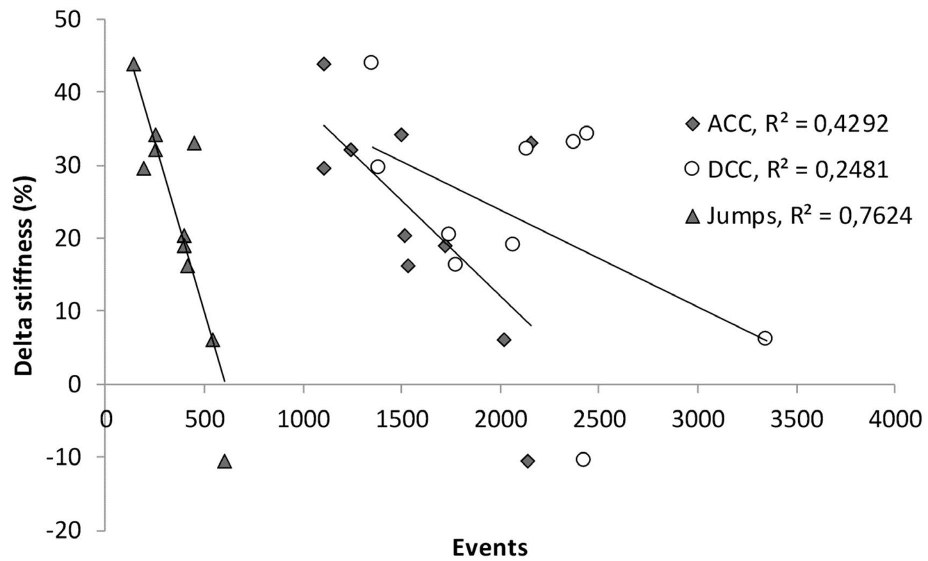

Figure 4. Relationship between acceleration (ACC), deceleration (DCC), and jump events and the increase of stiffness in hamstring muscles.

Table II. Passive hamstring stiffness, peak torque, and knee extension range of motion under different periods. Values are means ± SD.

Variable	Baseline	Pre-season	In-season	F	P	η^2
Passive stiffness, Nm/degrees	1.37 ± 0.08	1.48 ± 0.8	1.68 ± 0.05*	5.788	0.011	0.391
Normalized passive stiffness	0.025 ± 0.001	0.028 ± 0.003	0.031 ± 0.003*	6.014	0.010	0.401
Passive peak torque, Nm	55.98 ± 3.69	55.55 ± 3.50	56.10 ± 4.02	0.012	0.988	0.001
ROM, degrees	88.22 ± 2.02	89.23 ± 2.00	89.85 ± 1.95	0.545	0.589	0.057
*P, significance value; η^2, partial eta squared; *, significantly different compared with the baseline value.*						

Table III. Peak concentric and eccentric torque of knee flexors, and peak concentric torque of knee extensors at different speeds and under different periods. Values are means ± SD.

Variable	Baseline	Pre-season	In-season	F	P	η^2
Concentric knee flexion, Nm						
60°/s	118.74 ± 17.28	128.27 ± 16.80	130.46 ± 10.61	1.965	0.169	0.179
180°/s	94.55 ± 10.24	104.57 ± 11.57	107.37 ± 9.82*	5.672	0.012	0.387
Eccentric knee flexion, Nm						
60°/s	177.31± 30.06	167.31 ± 32.72	156.11 ± 27.72*	4.431	0.027	0.330
180°/s	174.10 ± 30,81	148.71 ± 22,05	141.82 ± 22.47*	8.043	0.006	0.573
Concentric knee extension, Nm						
60°/s	235.34 ± 43.84	219.62 ± 52.23	221.23 ± 10.82	0.860	0.440	0.087
180°/s	180.13 ± 24.89	172.28 ± 21.19	171.54 ± 23.40	1.389	0.275	0.134
*P, significance value; η^2, partial eta squared; *, significantly different compared with the baseline value.*						

Repeated-measures ANOVA showed a significant impact of training period on hamstring passive stiffness (F=5.788, P=0.011) and normalized passive stiffness (F=6.014, P=0.010) (Table II). A pairwise comparison showed a significant increase in hamstring passive stiffness and normalized passive stiffness after the in-season period compared with the baseline (P=0.044 and P=0.049, respectively). However, passive peak torque and ROM did not change after either the pre-season or in-season periods.

The change in the relative hamstring passive stiffness during the in-season period was negatively correlated with acceleration (r=−0.655, P=0.040, 95% CI -0.039 to -0.854) (Figure 4) and jump (r=−0.873, P=0.001, 95% CI -0.443 to -0.854) events. The strength of the correlation between the changes in the relative hamstring passive stiffness and acceleration events, and jumps varied according to acceleration intensity: the strongest significant correlations were at low (1–2 m/s^2) acceleration intensity (r=−0.663, P=0.037, 95% CI -0.052 to -0.855) and at low (0–20 cm) jump intensity (r=−0.899, P<0.001; 95% CI -0.494 to -0.762).

Repeated-measures ANOVA showed a significant impact of training period on the peak concentric torque of knee flexors at 180°/s (F=5.672, P=0.012) (Table III). A pairwise comparison indicated a significant difference in the peak concentric torque of knee flexors after the in-season period compared with the baseline (P=0.015). The training periods negatively affected the peak eccentric torque of knee flexors at different speeds of contraction (60°/s: F=4.431, P=0.027; and 180°/s: F=6.816, P=0.011). The peak eccentric torque of knee flexors after the in-season period was significantly decreased compared with the baseline at both the 60°/s and 180°/s speeds (P=0.036 and P=0.042, respectively). The peak concentric torque of knee extensors did not change significantly during the training periods.

Discussion

The purpose of the study was to identify changes in hamstring passive stiffness during the pre-season and in-season periods. The results show that the hamstrings passive stiffness significantly increased after 10 weeks of training, including pre- and in-season periods, and that the changes in the hamstrings passive stiffness are negatively correlated with EL characteristics such as accelerations and jump events.

The different levels of the applied loading conditions and general exercise conditions may considerably affect connective tissue adaptive responses[31]. We found that the change in muscle passive stiffness recorded during the in-season period was related with acceleration events and jumps rather than with deceleration events. The relationship detected between the increase in passive stiffness of the hamstrings and acceleration events and jumps can be explained by the muscle activity pattern during running and landing. During sprint accelerations, horizontal force production is predominantly determined by hamstring strength and biceps femoris (BF) EMG activity during the end-of-swing phase[32]. The BF shows high activation before and after foot contact, while the medial hamstring (MH) shows high activation during the late stance and mid-swing phases[33]. During the preparation of landing for the vertical stop-jump task, hamstring EMG rapidly increases over the late portion of the flight phase. The hamstrings stay active after landing, during the deceleration phase[34]. The activity of hip extensors changes depending on the acceleration phase. At the initial acceleration (first 10 steps), the EMG activity of the gluteus contributes to the generation of a horizontal force that is greater than the BF activity[32,35].

There are limited data in the literature regarding the mechanisms of hamstring muscle–tendon complex adaptations to lasting (more than 8 weeks) training stimuli. However, it is known that chronic overload, overstretching, and keeping a muscle in a shortened state all initiate an increase in the passive stiffness of skeletal muscles[22,36–38]. Increased passive stiffness can be facilitated through increased extracellular matrix volume by increased synthesis of collagen[39,40], reorientation of collagen fibers[41], changes in extracellular matrix chemistry and fiber cross-linking[42,43], and changes in tissue fluids[44].

In our study the average EL in-season period was 2272±243 A.U./week. The average IL expressed by RPE decreased from 2256 to 1471 A.U./week, reflecting increased players' fitness[2]. During the training periods, passive stiffness of the hamstring and the peak concentric torque of knee flexion at 180°/s was significantly increased showing adequate biomechanical and physiological adaptation of the muscles (Table II and III). However, we found that for a player, who EL exceeded 10896 A.U. and performed 2136 accelerations, 2430 decelerations and 604 jumps during the four weeks of training, the passive elastic stiffness of the hamstring was reduced. Excessive stimulation may slow the adaptation of the elastic components of the hamstrings. It was shown that adding exercise repetitions (cumulative load) did not increase collagen synthesis further (fibroblasts are unable to further synthesize collagen beyond this upper limit), but potentially increased the degradation and further amplified the negative net balance of collagen (balance between collagen synthesis and degradation)[45]. Spiesz and colleagues[46] reported an overloading increase in collagen breakdown and indicated a rapid inflammatory response from tendon cells immediately after overload. Interestingly, both the remodeling of inflammation and damage-induced matrix appear to be more concentrated in the interfascicular matrix compared with the fascicles[46]. We can speculate that, when training sessions are too stressful, athletes may not maximize the benefit of stimulated collagen synthesis; rather, it is likely to be in the net state of collagen catabolism[47]. In our study, the comparison of the loads of players showed that athletes with reduced hamstring passive stiffness after the in-season period performed 1.4 times more acceleration events and three times more low jumps than the group average. However, the hamstring muscle strength of players did not differ from the group average either in the concentric or in the eccentric contraction mode.

We found that the increase in hamstring passive stiffness was not related with knee ROM and passive peak torque. This implies that a typical workout (without any special or additional exercise for flexibility) during the pre-season and in-season periods does not change the stretching amplitude and tensile force of the hamstrings but increases passive hamstring stiffness. Passive muscle stiffness is not uniquely associated with ROM. A previous study showed that the improvement in flexibility recorded over 4 weeks of stretching training was associated with changes in the perception of pain, rather than the physical properties of the hamstrings, with passive muscle stiffness measured over the same angles (50%–80% of maximum ROM) used for the pretraining measurements[48]. However, a 6-week stretching program significantly increased the knee extension ROM and hamstring passive stiffness in the new ROM (the stiffness for the final 10% of the ROM)[22]. This emphasizes that passive muscle stiffness is different from ROM and that the knee extension angle should not be used in the evaluation of the stiffness of the hamstring muscle.

To explain the observation of increased muscle passive stiffness without changes in ROM and passive peak torque, we hypothesized that the training induced changes in the internal structures of the tendon and/or aponeurosis, and/or extracellular matrix[11,31]. It is very important to note that tendon stiffness adaptation is the time-course of training[49–51] and requires 8–12 weeks of intervention[18–20]. In our study, hamstring passive stiffness did not increase significantly after 4 weeks of pre-season training but reached statistical significance at the end of the 10-week training period. These findings highlight the importance of controlling soft tissue adaptation rate in relationship with the acute and chronic workload ratio[9] during the pre-season and in-season periods. This could avoid the gap between physiological and biomechanical adaptation to the training load and reduce non-contact, soft-tissue injuries.

The results of our study showed that the peak eccentric torque of knee flexors was significantly decreased at speeds of 60°/s and 180°/s in the training period. Weakness of hamstring muscle eccentric contraction and the decreased stiffness of the passive elements are factors that can increase the risk of muscle–tendon unit injury[16,17]. The decline in eccentric strength is possibly related with cumulative training and competition loads or training specificity, which place soccer players in unfavorable conditions. The cumulative load during a season can slow down the adaptation of the elastic components because of increased collagen degradation, which reduces the muscle passive stiffness and increases the risk of hamstring muscle injuries in professional soccer players. The monitoring of the training loads, muscle eccentric strength, and passive stiffness can be included in the various programs aimed at the prevention of hamstring injuries. However, we did not record injury incidents, as a much larger sample size is needed to address this question adequately. We also have recorded only biceps femoris activity during muscle passive stiffness measurements and therefore the lack of control of semitendinosus and semimembranosus activity could be viewed as a limitation in current study.

Conclusions

The hamstring passive stiffness of professional soccer players significantly increased after 10 weeks of training, including the pre-season and in-season periods, without changes in passive stretching torque and ROM. The changes in the hamstrings passive stiffness appear negatively associated with acceleration and jumping events amount of external load. It also remarkable that rather small increase in hamstring passive stiffness was achieved in players who performed largest amount accelerations and jumps suggesting negative biomechanical adaptation to excessive mechanical stress.

What does this article add?

Previous studies have identified the importance of external factors, such as player load in pre-season and in-season on likelihood of hamstring injuries[4]. High compliance of the muscle's extracellular matrix or tendon can increase the amount of muscle fiber strain consequently causing muscle damage or injury[14,15]. We found that regular training and match workouts increase hamstring passive stiffness within 10 weeks in professional soccer players. However, the individual changes in the hamstring passive stiffness are related to the amount, character and intensity of cumulative external load. For the first time we show that adaptation of muscle-tendon unit passive elements could slow down or might not occur if players perform too many jumps and acceleration events. Regular assessment of hamstrings passive stiffness modifications during the season could help identify critical moments for each player and reduce the risk of hamstring overstrain injuries.

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