ORIGINAL ARTICLE

Effects of underweight-plyometric training on the neuromuscular characteristics in professional rugby players

Enrico REJC [1], Mirco FLOREANI [2, 3], Filippo VACCARI [2, 3] *, Nicola GIOVANELLI [2, 3], Alberto BOTTER [2, 3], Alessandro GANZINI [2, 3], Stefano LAZZER [2, 3]

[1]Kentucky Spinal Cord Injury Research Center, University of Louisville, Louisville, KY, USA; [2]Department of Medicine, University of Udine, Udine, Italy; [3]School of Sport Sciences, University of Udine, Udine, Italy

*Corresponding author: Filippo Vaccari, Department of Medicine, University of Udine, Piazzale Kolbe 4, 33100 Udine, Italy. E-mail: filippo.vaccari@uniud.it

ABSTRACT

BACKGROUND: Many sport performances are influenced by maximal muscular power. Stereotyped training stimuli progressively reduce their potential to improve the neuromuscular factors contributing to maximal muscular power. Herein, we investigated the effects of substituting a standard resistance training with a plyometric training performed in a condition equivalent to about half body weight (UP training) on neuromuscular characteristics of the lower limbs in professional rugby players.
METHODS: Athletes were divided into two homogenous groups: the control group maintained its regular resistance training twice per week for eight weeks, while the treatment group substituted the regular resistance training with UP training on a sledge ergometer.
RESULTS: after UP training: 1) maximal explosive power of the lower limbs did not change significantly in squat jump, countermovement jump and drop jump; 2) maximal voluntary isometric contraction of plantar flexors substantially increased (+35.9%, P<0.001); and 3) vastus lateralis muscle architecture remained unvaried. In addition, the duration of the UP-training sessions was much shorter than the regular resistance training (15 min vs. 90 min on average).
CONCLUSIONS: UP training appears to be suitable for professional power athletes when strength and conditioning coaches aim at reducing training volume (i.e., tapering) while maintaining muscle power.

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KEY WORDS: Sports nutritional physiological phenomena; Team sports; Athletes; Physical functional performance; Resistance training.

Many sport performances are influenced by maximal muscular power. This is determined by the muscle force-velocity relationship and can be improved by increasing maximal isometric force and/or maximal shortening velocity, as well as optimizing the profile of the force-velocity relationship.[1, 2] Athletes' strength level dictates the upper limit of their potential to generate maximal muscular power; other abilities like generating force rapidly are of little benefit if maximal force is low.[3] Another important parameter is the athlete's window of adaptation (i.e. the magnitude of potential improvement) for each neuromuscular factor contributing to the maximal muscular power.[1] Indeed, although strength level substantially influences maximal muscular power, as maximal strength increases, the window of adaptation for further strength enhancement is reduced. Consequently, increments in maximal power output following traditional resistance training are expected to be lower in stronger individuals. In this type of athletes, more

velocity-specific exercises would impact primarily power output.[4] Plyometrics, which is a subcategory of ballistic exercises, is characterized by a rapid stretch-shortening cycle, during which the active stretching that occurs during the eccentric contraction of a muscle-tendon complex transfers energy to the following and immediate concentric phase.[5] This mechanism is exploited during locomotion and other activities such as hopping and throwing.[5] Typically, plyometric exercises are performed with little or without overloads (conditions equivalent to 0-60% of 1 RM).[6] Intensity of plyometric exercises can be modulated by the stretch rate (*i.e.*, changing the drop height during drop jump). Improvements in maximal muscular power following plyometric training are primarily due to positive adaptations in neural drive, rate of neural activation and inter-muscular coordination.[3, 4] Professional power athletes often combine resistance, ballistic and plyometric training depending on sport specificity, periodization, individual characteristics and physical trainer's background. As a matter of fact, the maximal muscular power of these athletes is relevant, and the window of adaptation for the neuromuscular factors that have been widely trained during their career span with classic training methods is narrow. The aim of this study was to investigate the effecwts of substituting a standard resistance training with a plyometric training performed in a condition equivalent to about half body weight on neuromuscular characteristics of the lower limbs in professional rugby players.

Materials and methods

Subjects

Neuromuscular data were collected on eighteen professional male rugby players of the "A1" Italian national championship. All players were "forwards," a role that requires muscle strength and power to push against opponents during scrums, rucks and mauls; to sprint, and jump during touches. The experimental protocol lasted from February to April 2019 (8 weeks in total), that is within the competitive season. This protocol was approved by the Ethics Committee of the University of Udine and conformed to the Dec-

laration of Helsinki. Before the study began, the purpose and objectives were carefully explained to athletes and physical trainer, and written informed consent was obtained from all athletes. Four athletes sustained an injury during official matches in this time window, and therefore were excluded from this study.

Study design

Training

Athletes were divided into two homogenous groups (control group [CTRL] N.=7; experimental group [EXP] N.=7;) by using the block randomization method.[7] The CTRL athletes maintained their regular resistance training twice per week, which consisted of squat (pyramid), deadlift, half squat (explosive) and squat jump (Tuesdays, 90 min); squat, clean, agility drills (Fridays, 30 min). They also performed an additional resistance training session per week (Wednesdays, 20 min), which was not focused on power exertion, and consisted in squats (pyramid). On the other hand, the two weekly resistance training sessions were replaced by UP training for EXP athletes, who also underwent the regular resistance training session. Each UP-training session lasted approximately 15 minutes and consisted of 3 to 5 sets of 8 to 10 consecutive plyometric efforts. Athletes were asked to exert the highest power at every jump. Rest between sets was 2 minutes. Time course of "volume" (number of repetitions) and "intensity" (number of bands) of the 15 UP training sessions is reported in Figure 1. To perform UP training, as well as some parts of the experimental sessions, the Explosive Ergometer (EXER) described by Rejc *et al.*[8] was used. EXER consists of a metal frame supporting one rail, which can be inclined up to 30 degrees. A seat, fixed on a carriage is free to move on the rail, its velocity along the direction of motion being continuously recorded by a wire tachometer (LIKA SGI, Vicenza, Italy). The total moving mass of the EXER (seat and carriage together) was equal to 31.6 kg. The athlete can accelerate himself and the carriage seat backward pushing on two force platforms (LAUMAS PA 300, Parma, Italy) that are positioned perpendicular to the rail. During training, the rail of EXER was in-
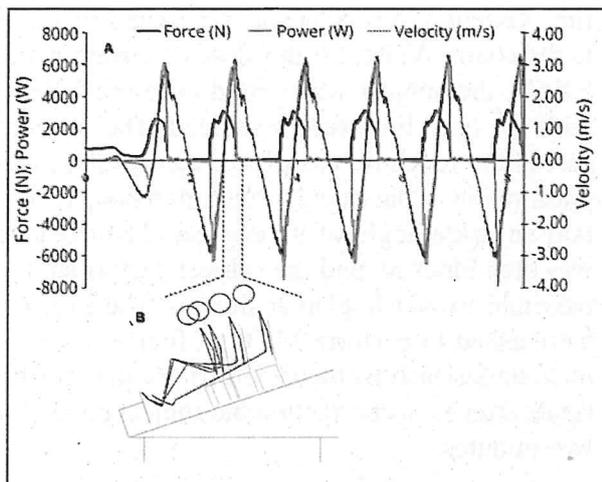
Figure 1.—Time course of force, velocity and power during a typical underweight-plyometric training session (A). Stick diagram representing an explosive lower limb extension performed by an athlete who was seated on the carriage seat of EXER during the underweight-plyometric training (duration: 300 ms) (B).

clined by 20 degrees. So, the force acting against the lower limb explosive extension was equal to about 45% of the average athletes' body weight. Furthermore, a series of resistance bands (Exercise Tubing silver, Thera-Band®, Ohio) were linked to the carriage seat and to the fix frame in front of it. Band length was set in order not to exert any braking force throughout the push phase (*i.e.*, until the lower limbs were fully extended). However, the eccentric part of the exercise (*i.e.*, landing) was potentiated by the elastic energy accumulated by the bands from the take-off to the most far point reached by the carriage seat while moving backward. The effect of four resistance bands is exemplified in Figure 2: the absolute values of peak power reached during the eccentric phase (negative peaks) were about 850
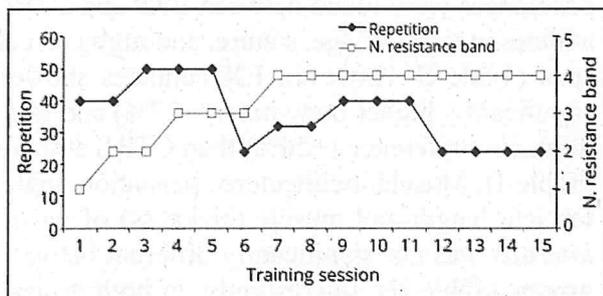

Figure 2.—Time course of "volume" (number of repetitions, filled diamonds) and "intensity" (number of resistance band, empty squares) throughout the 15 Underweight-Plyometric training sessions.

W higher than the peak power measured in the concentric phase (positive peaks).

Experimental sessions

The following measurements were carried out two days before the beginning of training (pre-training) and two days after the last training session (post-training).

Anthropometric characteristics

Body mass was measured to the nearest 0.1 kg with a manual weighing scale (Seca 709, Hamburg, Germany) with the subject dressed only in light underwear and no shoes. Stature was measured to the nearest 0.5 cm on a standardized wall-mounted height board. Mid-thigh circumference was measured by a metric tape midway between the greater trochanter and the lateral epicondyle of the femur.

Ultrasonography

Muscle architecture (muscle thickness, pennation angle and fascicle length) was measured in vivo on the vastus lateralis of the thigh (dominant limb) at rest, by means of a real-time B-mode ultrasonography (AU5; Esaote Biomedica, Florence, Italy) with a 92.3-mm, 7.5-MHZ linear-array probe. The accuracy of this methodology to assess muscle architecture measurements has been widely validated.[9, 10] Athletes were lying supine, with the knee joint in anatomical position, meaning passively fully extended.[11] Scans were acquired at 50% of muscle length, mid-belly, in the midsagittal plane. Pennation angle was calculated as the angle between the fascicle and the deep aponeurosis of the muscle. In each scan, the pennation angle of three fascicles was used for analysis.[12] Muscle thickness was defined as the distance between the deep and superficial aponeuroses, and the average of three measurements along the aponeurosis was used as indicative of the thickness.[11] Fascicle length was measured as the length of a fascicle between its insertions at the superficial and deep aponeurosis. Since fascicles extended beyond the recorded image, fascicle length was estimated from muscle thickness and fascicle pennation angle (θ) using the following equation:

$$\text{Fascicle length} = \text{muscle thickness} \sin \theta^{-1}$$

Image J software (National Institutes of Health, Bethesda, MD, USA) was used to analyze the ultrasonic images.

Lower limb explosive muscle contractions

Athletes were seated on the carriage seat of the EXER, the rail of which was inclined by 30 degrees. They were asked to perform three different exercises: squat jump (SJ), countermovement jump (CMJ), and drop jump (DJ). During SJ, two mechanical blocks were used to set the distance between the seat and the force platforms, so that knee angle at rest was 110 degrees. The blocks also prevented any countermovement and, consequently, any recovery of elastic energy during the pushing phase. During CMJ the mechanical blocks used to prevent countermovement in SJ were removed. Athletes placed the soles of their feet against the force platforms, with the knee joint fully extended. From this position, athletes were asked to perform a countermovement jump. To perform DJ, athletes placed the soles of their feet against the force platforms with the knee joint fully extended. Then, two operators moved the carriage seat 0.5 m backward. After a countdown, the operators left the carriage seat which moved forward, so that athletes were able to perform DJ. Athletes performed three maximal attempts for each of the three tasks (SJ, CMJ, DJ), with a 2-minute rest in between each effort. The average peak power value calculated among the three attempts for each task (maximal power, MP) was considered for further analysis.

Isometric contractions

The isometric contractions were performed with the dominant lower limb. The athletes were seated on either a special chair[8] or the EXER. As far as the athletes seated on a special chair, the athlete was seated with the legs hanging vertically down. A strap was tightened around the athlete's right ankle and was linked by means of a steel chain to a fix frame. The chain length was set to obtain a knee angle of 110 degrees.[13] The fix frame was positioned behind the ankle to perform the isometric knee extension, whereas it was in front of it for the isometric knee flexion. A force sensor (TSD121C, BIOPAC Systems,

Inc., Goleta, CA, USA) was connected in series to the chain. While, for the athletes seated on the EXER, the subject was seated onto the EXER, with the right limb fully extended. The forward part of the foot sole was placed against the force platform in a flat standardized position, to obtain an ankle angle of 90 degrees. The carriage was then blocked, and the subject performed the maximal isometric plantar flexion. The subjects were asked to perform MVC of four – five seconds under each isometric effort. To prevent fatigue, after each contraction the subject rested for two minutes.

Statistical analysis

Statistical analyses were performed using PASW Statistic 18 (SPSS Inc., Chicago, IL, USA) with significance set at $P<0.05$. All results are expressed as means and standard deviation (SD). Normal distribution of the data was tested using the Kolmogorov-Smirnov Test. Sphericity (homogeneity of covariance) was verified by the Mauchly's Test. Changes of anthropometrics characteristics, MVC, muscle architecture and MP were studied with a general linear model repeated measures considering two factors (grouP=EXP *vs.* CTRL; time: PRE *vs.* POST) and interaction (group × time). When significant differences were found, a Bonferroni *post-hoc* test was used to determine the exact location of the difference.

Results

Athletes' physical characteristics and vastus lateralis muscle architecture

Prior to the beginning of training, no significant differences were found between EXP and CTRL athletes in terms of age, stature, and rugby career span (Table I). However, EXP athletes showed significantly higher body mass (+27%) and mid-thigh circumference (+20%) than CTRL athletes (Table I). Muscle architecture (pennation angle, fascicle length and muscle thickness) of *vastus lateralis* was not significantly different between groups (Table II). Interestingly, in both groups, no significant changes in any of these parameters were detected by comparing pre and post training time points (Table I, II).

TABLE I.—*Characteristics of experimental (EXP, N:7) and control (CTRL, N:7) athletes, before (Pre) and after (Post) the period of training.*

	EXP			CTRL			P		
	Pre-	Post-	Δ (%)	Pre-	Post-	Δ (%)	Group	Period	G×P
Age (year)	23.9±2.8	-	-	21.6±0.8	-	-	0.053	-	-
Stature (m)	1.84±0.09	-	-	1.79±0.06	- ·	-	0.208	-	-
Body mass (kg)	106.1±4.3	105.5±3.7	-0.6	83.6±8.1	82.9±7.6	-0.8	0.001	0.157	0.898
Mid-thigh circumference (cm)	66.8±3.7	67.8±2.8	+1.5	55.7±8.3	54.7±7.9	+1.8	0.003	0.978	0.070
Rugby career span (year)	12.3±6.3	-	-	11.7±4.4	-	-	0.847	-	-
Professional rugby career span (year)	4.1±2.4	-	-	3.4±0.5	-	-	0.459	-	-

All values are reported as mean±standard deviation.
ΔPercent difference between post and pre training.

TABLE II.—Vastus lateralis *architecture: maximal voluntary isometric contraction during knee extension/flexion and plantar flexion; and maximal power during squat jump, countermovement jump and drop jump before (pre-) and after (post-) the period of training in the experimental (EXP, N:7) and control (CTRL, N:7) athletes.*

	EXP			CTRL			P		
	Pre-	Post-	Δ (%)	Pre-	Post-	Δ (%)	Group	Period	G x P
Pennation angle (deg)	20.9±2.9	22.3±1.5	+6.4	23.7±2.3	21.1±2.1	-10.8	0.522	0.412	0.098
Fascicle length (cm)	8.05±0.9	7.4±0.9	-7.9	7.1±1.4	7.2±1.6	+1.0	0.384	0.235	0.146
Muscle thickness (cm)	2.9±0.3	2.8±0.3	-1.8	2.8±0.4	2.6±0.3	-7.8	0.409	0.102	0.184
MVC knee extension (N)	894±75	929±83	+3.9	941±106	887±142	-5.7	0.962	0.682	0.071
MVC knee flexion (N)	350±37	377±76	+7.7	413±74	348±84	-15.7	0.648	0.431	0.078
MVC plantar flexion (N)	1694±173	2302±219*	+35.9	1768±370	1733±449	-2.0	0.189	0.001	0.001
MP SJ (W)	5398±839	5443±861	+0.8	5630±767	5437±562	-3.4	0.771	0.630	0.441
MP CMJ (W)	6106±545	5670±713	-7.6	5435±838	5178±661	-4.7	0.129	0.076	0.423
MP DJ (W)	6464±533	5882±562	-9.0	5631±714	5420±704	-3.7	0.076	0.054	0.126

Values are reported as mean±standard deviation.
MVC: maximal voluntary isometric contraction; MP: maximal power; SJ: squat jump; CMJ: countermovement jump; DJ: drop jump; EXP: experimental.
ΔPercent difference between Post and Pre training; *significantly different pre- vs. post- ($P<0.05$).

Maximal voluntary contraction

Prior to the beginning of the training period, no significant differences were found between EXP and CTRL athletes on maximum isometric force generated by knee extensors, knee flexors, and plantar flexors (Table II). After UP training, EXP athletes substantially increased the force generated during plantarflexion MVC (+35.9%, $P<0.001$). Also, EXP athletes tended to generate higher isometric force during knee extension and flexion (+3.9% and +7.7%, respectively, see Tab. II). Interestingly, CTRL athletes presented an opposite trend, as force generated during MVC of plantar flexors, knee extensors and knee flexors tended to decrease by 2.0%, 5.7% and 15.7%, respectively (Table II).

Maximal Power

Prior to the training period, MP generated during SJ and CMJ was similar between the two groups, while it was significantly higher in EXP athletes for DJ (+13%, $P=0.030$; Tab. II). EXP athletes also generated higher MP during DJ (+20%, $P=0.022$) and CMJ (+12%, $P=0.014$) as compared to SJ (Tab. II). Conversely, no significant differences across these three different explosive movements were found in CTRL athletes. Importantly, MP generated by both groups was similar at Pre and Post UP training for all three tested explosive exercises (SJ, CMJ and DJ, Tab. II). Furthermore, no significant Exercise x Time interactions were found (Table II).

Discussion

The substitution of a standard resistance training with UP training: 1) did not lead to architectural changes in the vastus lateralis muscle; 2) substantially increased the MVC of plantar flexors; and 3) maintained similar levels of MP of lower limbs during explosive exercises without

and with different degrees of elastic energy recovery, while substantially reducing the training duration.

Vastus lateralis muscle architecture was not altered after UP training

Plyometric training has been shown to improve muscle power without leading to muscle hypertrophy.[4, 14] Our results support this perspective, as UP training did not modify muscle thickness of a primary lower limb extensor muscle (VL). Body weight and mid-thigh circumference were also unvaried after UP training. Muscle thickness of VL is directly proportional to its cross-sectional area and can be used in monitoring long-term hypertrophic responses.[15, 16] Hypertrophy occurs in response to mechanical tension in a range of resistance training conditions[17] such as traditional resistance training.[4] However, plyometric training may also lead to muscle hypertrophy in non-professional athletes' populations such as untrained individuals,[18] very young (11-13 y) soccer players without previous experience in strength training,[19] active but non-athlete individuals,[20, 21] and in older people.[21] On the other hand, the subjects tested in this study were athletes with an advanced training status, thus explaining why neither the continuation of regular resistance training nor UP training led to muscle hypertrophic adaptations of VL.[1, 4] The lack of training-induced VL morphological adaptations may also be due to the lower ground reaction forces experienced during underweight-plyometric training as compared to the regular DJ. Along with muscle thickness, pennation angle and fascicle length are also important factors for determining the muscle mechanical output. Pennation angle may be indicative of addition of sarcomeres in parallel[22] and increases following heavy strength training.[4, 23] Conversely, sprint and jump training significantly decreases this parameter.[24] Plyometric training was recently shown to promote an increased pennation angle of *vastus lateralis* in physically active individuals and in older people.[21] This finding further suggests that professional athletes respond differently than less fit individuals to plyometric training. Finally, fascicle length can increase in response to sprint training[25] but also following resistance training with heavy and light loads[4] as well as in subjects who interrupt strength training to perform jump and sprint training.[24] This adaptation is considered to reflect an addition of sarcomeres in series[22] and to be a determinant variable for maximal contraction velocity.[26] Muscle fiber maximal shortening velocity depends on fiber types and it is proportional to its length.[26] In the present study, fascicle length was also not significantly affected by UP training; similar findings were reported in other longitudinal studies following heavy strength training which involved subjects in an advanced training status.[27, 28] The lack of training effects on these muscle architecture characteristics may be conceivably due to the training status of our research participants, which may have mitigated the potential changes in VL muscle architecture that UP training may induce.[1] A limitation of the present study is that we did not assess the muscle architecture of plantarflexor muscles, which showed the greater increment in force generation after UP training.

UP training increased the maximal voluntary strength of plantar flexors

One of the most relevant effects of UP training was found in plantar flexors MVC, which increased by 36% after training; conversely knee extensors and flexors MVC did not change significantly in response to either training modality. Other studies showed an improvement of MVC following plyometric training in plantar flexors[20, 29] and in knee extensors[21, 29] while assessing less fit (*i.e.*, non-professional athletes) individuals. Of particular interest is the study of Staniszewski *et al.*,[29] which assessed the effects of more pronounced concentric *versus* more pronounced eccentric plyometric training on MVC. They reported that only the more concentric-focused paradigm promoted an increased MVC of knee extensors, while both training paradigms promoted higher levels of plantar flexors MVC. Taken together, these findings may suggest that lower limb plyometric training more oriented toward the eccentric phase is particularly effective for improving plantar flexion force generation, irrespectively of the individuals' training status. Changes in MVC are mainly determined by variation of cross-sectional area, level of neu-

ral activation and muscle intrinsic force (force / cross sectional area).[30] As mentioned above, muscle architecture of plantar flexors was not examined in this study; thus, we cannot provide an insight about the mechanisms related to the observed training-induced increment in plantarflexion MVC. Changes in neural factors were shown to be predominant after plyometric training.[4, 14] However, jumps performed on a sledge ergometer result in a reduced neuromuscular activation during the preactivation and reflex activation phases as compared to regular, vertical jumps.[31] Hence, UP training-related gains may be substantially attributable also to changes in mechanical properties.[20] Prior UP training, the athletes enrolled in this study often performed exercises involving knee extensors but did not perform any training aimed at improving specifically the plantar flexors motor output. Hence, their wider window of adaptation may have amplified the positive effect of the complete and robust plantarflexion performed at every jump during UP training.[32]

UP training maintained the maximal explosive power of lower limbs

UP training maintained the MP exerted during SJ and CMJ and DJ. This finding is noteworthy because UP training, which substituted the regular resistance training, reduced substantially the training volume (approximately 15 min *vs.* 90 min) while maintaining MP of lower limbs during the competitive season. Hence, UP training may be suitable for specific periods of the sport season during which physical trainers plan to reduce training volume while maintaining intensity (*i.e.,* tapering).[33] In addition, it has been shown that plyometric training added to regular training improved jump performance as well as some aspect of repeated sprint ability in handball players.[34] These positive effects were probably due to an increased tendon stiffness[35] or overall joint stiffness,[20] thus allowing muscle-tendon complex to better exploit elastic energy.

Conclusions

In conclusion, the increment of force exerted by plantar flexors after UP training is a relevant ad-

aptation for rugby players, especially during specific phases of the game like mauls, where athletes exert maximal force levels pushing against the opponents. The very short duration of UP training makes it suitable for periods of the sport season during which physical trainers consider reducing training volume (*i.e.,* tapering) in order to recover from fatigue while maintaining or improving muscle power.

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